Introduction to Geological Processes in New Zealand,

Auckland area

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Introduction

Below is the Achievement Standard statement

Subject Reference Earth and Space Science 2.3

Title Investigate geological processes in a New Zealand locality
Internal (Field trip and test) 4 credits

Achievement Criteria

Achievement	Achievement with Merit	Achievement with Excellence
• Investigate geological processes in a New Zealand locality.	• Investigate in depth geological processes in a New Zealand locality.	• Investigate comprehensively geological processes in a New Zealand locality.

Explanatory Notes

1 *Investigate* requires the student to:

- identify the types of rock(s) found in the locality
- describe the plate tectonic and rock cycle processes that have formed the types of rocks in the locality
- describe the erosional processes that have shaped the current landforms in the locality.

Investigate in depth is further developed by:

- explaining the plate tectonic and rock cycle processes that have formed the types of rocks in the locality
- explaining the erosional processes that have shaped the current landforms in the locality.

Investigate comprehensively is further developed by:

- discussing the link between the plate tectonic processes and the rock cycle processes that have formed the types of rocks in the locality
- discussing the link between the erosional processes with the shape of the current landforms in the locality.

2 *A New Zealand locality* is considered to be anywhere within the Zealandia continent.

3 *Geological processes* will include:

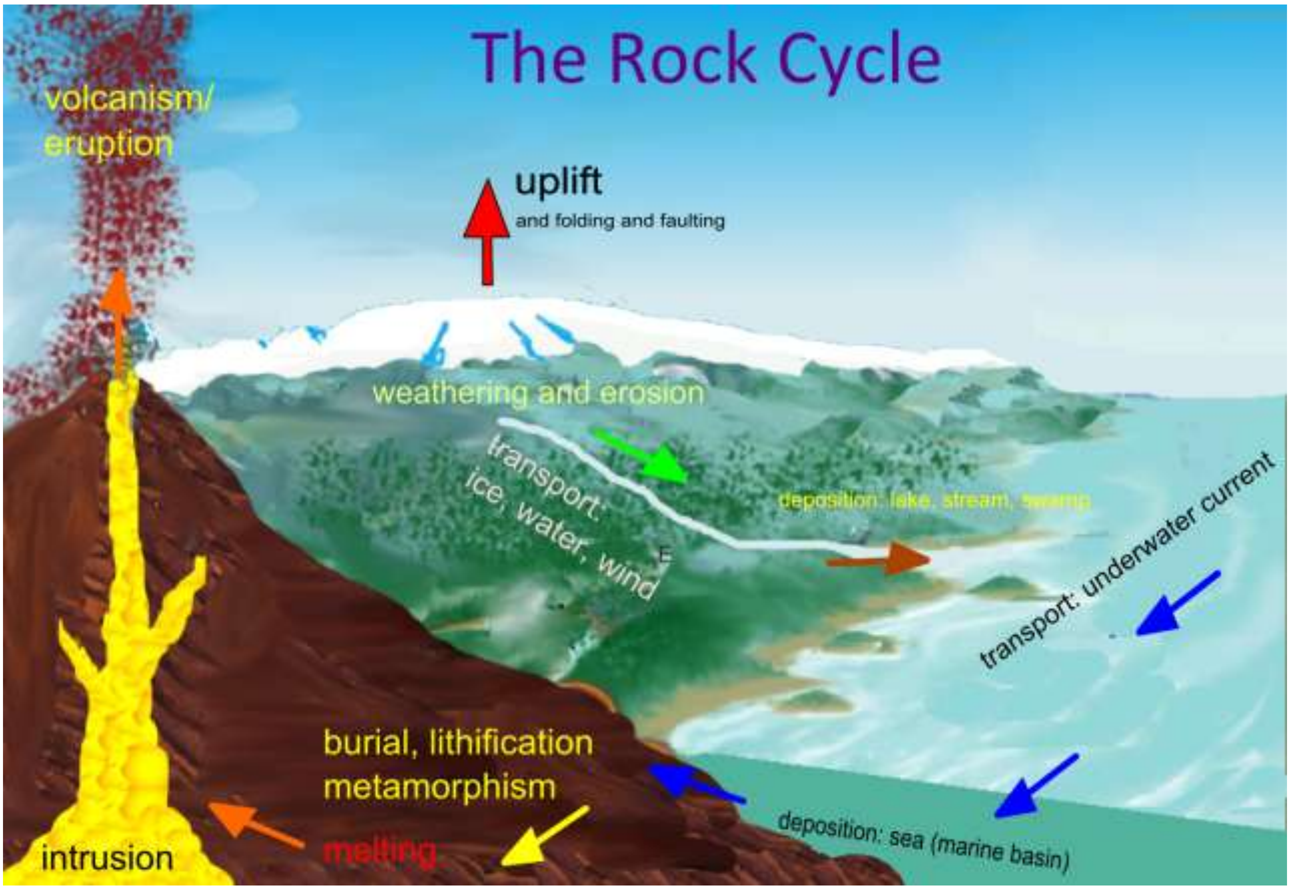
- plate tectonics and the rock cycle
- erosion.

Different parts of this booklet are set out in different ways.

- The main information is given in the body text.
- Additional or “interesting” information is given in text boxes set within body text.
- Practical activities are in grey boxes.
- Note-taking activities, to help you remember, are in a different font and surrounded by a double line.
- Reinforcement exercises and questions from old exam papers are in a separate section at the end of each chapter.

Chapter 1: The Rock Cycle and geological time

The rocks and landforms we see around us come about as a result of the processes acting on and within the earth: weathering, erosion, transport, deposition, burial, lithification, metamorphism, melting, intrusion, eruption, uplift, deformation. These processes make up the **rock cycle.** They can be represented in diagrammatic form as shown below. We will examine them one by one.



Chemical weathering in basalt (brown rind to rock) *Wiki image*

Weathering

Weathering means the breakdown of rock into smaller fragments or dissolved minerals.

Chemical weathering means changes in minerals due to exposure to air and/or water. One obvious sign of this is a change in colour, such as a brown colour caused by oxidation of iron. Other changes caused by chemical weathering can do several things:

- Some minerals may dissolve away, which can leave others as unsupported grains to be washed away.
  Dissolved minerals are mostly washed into the sea, although some may crystallize out elsewhere e.g. around Auckland it is common to see concretions made of the mineral *limonite,* a hydrated iron oxide mineral formed from iron ions dissolved in groundwater.
- Some minerals may change their composition and this may involve a change of volume and

Chemical weathering of limestone resulted in these formations at Punakaiki

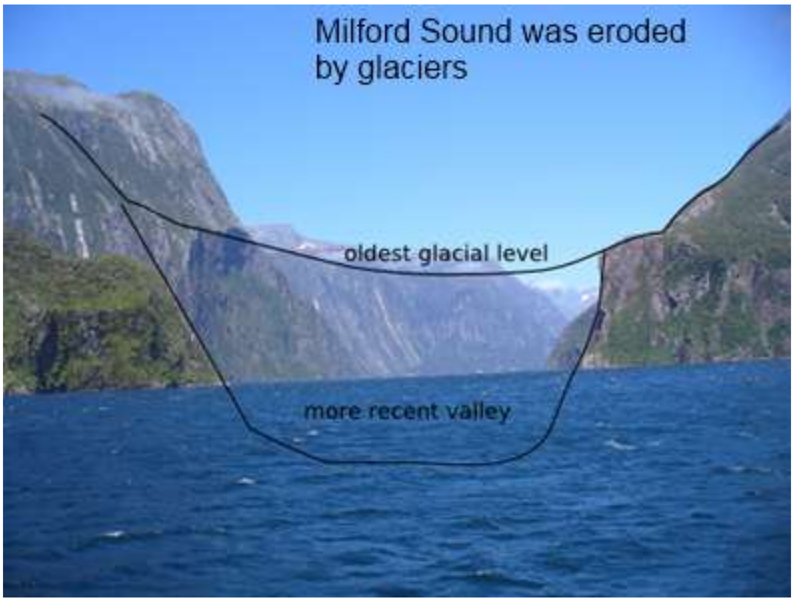
or hardness, also leaving other mineral grains unsupported to be washed away.
Examples of this are feldspar minerals changing into soft clay minerals, or volcanic minerals changing into oxides and hydroxides which are much softer. You can see the effects of chemical weathering on the outside surface of many rocks.

Physical weathering is the breaking up of rock, with fragments being physically moved apart. This can be caused by:

- water freezing in cracks in the rock,
- plant roots forcing cracks apart,
- swelling minerals like clays expanding between grains as they get wet and dry out
- expansion and contraction of the rock due to heating and cooling over the day and night. This produces cracks which allow the other processes to happen.
- Salt or other mineral crystals forming in cracks in the rock; this is particularly common in porous rocks, such as sandstone, on the sea shore such as sandstone

Erosion:
This is the removal of broken up material, and is combined with transport. The rate of erosion increases with rainfall and mountain height (relief). This means that the highest mountains are in the places of greatest uplift, as mountains will grow until the rate of uplift and the rate of erosion are equal. For example, the most rapid uplift in NZ is occurring near Mt Cook.
Also, certain places are prone to particular types of erosion. Shoreline erosion takes place from low to high tide levels. The shore very often is eroded back into a bench called a **shore (**or **wave cut) platform.**

Wave cut platform showing a fold in layered rocks, Blockhouse Bay. Cliffs in the background would originally have sloped down to a shallow stream valley before being cut back.



Transport
This is where weathered and eroded material, together with material like volcanic ash and plant fragments, is moved by water, wind or mass movement. More detail on these processes is given in the section on sedimentary rocks.

Deposition
This is when transported material is deposited. Most transported material ends up on the continental shelf or the area between the continental shelf and the deep ocean. However, some gets deposited in other places like swamps, river deltas, lakes, desert dunes and valleys.

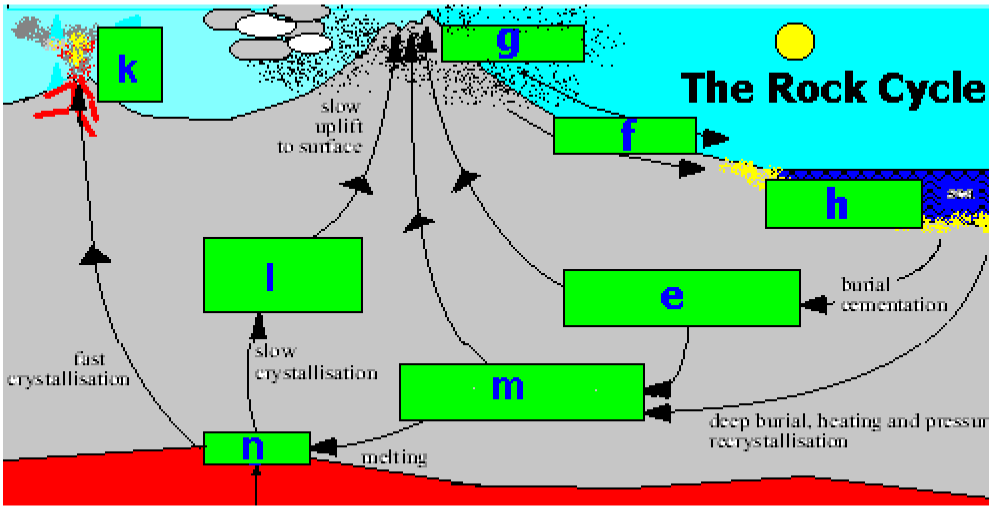
Deformation and uplift:
Deformation means **folding** and **faulting**. Rock strata can be bent, or can fracture so they are offset vertically or horizontally (or some combination of the two). Often, parallel or perpendicular sets of faults combine upwards and downwards movement to form fault blocks. The Hunua Ranges, near Auckland, are such a fault block.

Uplift is the product of upfolding and upfaulting**.** Together, these processes are responsible for **mountain building** (or **orogeny**; from the Greek 'oros' = mountain and 'genos' = to make.

Intrusion:
Magma usually rises towards the surface, but doesn't always reach it. Even where it erupts to form volcanoes a major proportion of it still remains underground. The 'plumbing' of volcanoes is often all that is left after millions of years of uplift and erosion have removed the overlying volcanic rocks. It can be in the form of large **plutons** (see the section on igneous rocks for an explanation of this), or of volcanic pipes, or vertical or horizontal "walls" of magma (called dikes and sills respectively).
An intrusion is **always** younger than any strata that it intrudes or cuts across (this is one of the 'rules' geologists use when working out which is the oldest rock in a series).

Eruption:
This is where molten rock (**magma**) from deep inside the earth reaches the surface. Eruptions can be **explosive**, with material being thrown out, or **effusive** with material pouring out from a vent (lava flows). Most magma contains a lot of dissolved gas, mostly carbon dioxide and water (water is a gas at volcanic temperatures). If this cannot escape quickly it will blast the magma apart into droplets or fragments called **ash**. The ash bearing gas is usually very hot (> 800°C) and is therefore lighter than air. It rises until it cools enough for the ash to drop out of it. Ash can be carried high enough to reach stratospheric winds and be deposited thousands of kilometers away from the volcano.

Complete the exercises below:



1. Match each of these processes with a letter on the diagram above (where applicable) and explain each of the following terms:

Chemical weathering, letter g; breakdown of rock due to air and water
Physical weathering, also g; physical breakdown of rock
Erosion wearing away of rock
Transport movement of weathered and eroded material
Deposition when the transported material stops moving
Burial when the deposited material gets covered up with more stuff
Uplift is when the buried stuff gets raised up as mountains (and then often worn away again, exposing older rocks)
Volcanism eruption of molten rock
Intrusion when molten rock squeezes into existing rocks
Lithification the conversion of sediment into rock by cementation and other processes

2. List 3 different natural transport methods for eroded material.

Water, air, ice, mass movement

3. In the sea, rates of deposition are highest near river mouths and very low far from land. Why is this?

Because the rate of deposition is 'opposite' to the current speed. Deposition is slowest where the current is fastest. As a river reaches the sea, the currents slow down. Most of the material is deposited, leaving progressively less to be deposited at greater distances.

4. Why do sedimentary rocks in the sea become finer grained further away from land?

Similar to above; the current speeds drop away from land and only the finest particles (fine muds) can remain suspended in the water to be carried out to sea.

5. Why are the highest mountains found where the rate of uplift is greatest? Explain.

A mountain will grow until the rate of erosion is equal to the rate of uplift. The higher the mountain, the faster it is eroded so it takes a higher rate of uplift to 'keep up'.

6. The rocks in central Otago have been uplifted about 14 km. Why aren't the mountains there 14 km high?

Because nearly all of that 14 km has been weathered, eroded, transported and deposited elsewhere as sedimentary rock.

1.2 Geological time

Even in ancient times, people noticed strange occurrences such as impressions of fish in rock strata far away from the sea or high up on mountains, or the bones and impressions of 'giant lizards' preserved in the rocks. Before the development of modern scientific thinking, explanations for this were based on myths, such as those of dragons, or on religious traditions, such as the Flood story in the Old Testament of the Bible.

As scientific thinking and understanding developed, people eventually came to think that these rocks and fossils were formed by the processes of the rock cycle that we still see going on around us. They theorized that these events had happened over a truly huge period of time.

Early geologists had no idea how much time was involved. However, they were able to work out which rocks were older or younger than others by applying a very simple rule:

In a series of rock layers, the layer on the bottom is the oldest.

(geologists call this the *rule of superposition).*

This rule can be used for much more than just a set of layers one on top of the other. In the diagram below, showing the rocks of Port Waikato, the rocks are folded into a large **syncline**. We can't see the rocks below the ground, but it is quite easy to *infer* what is there from the fact that matching sets of rocks and fossils appear on both sides of the syncline:

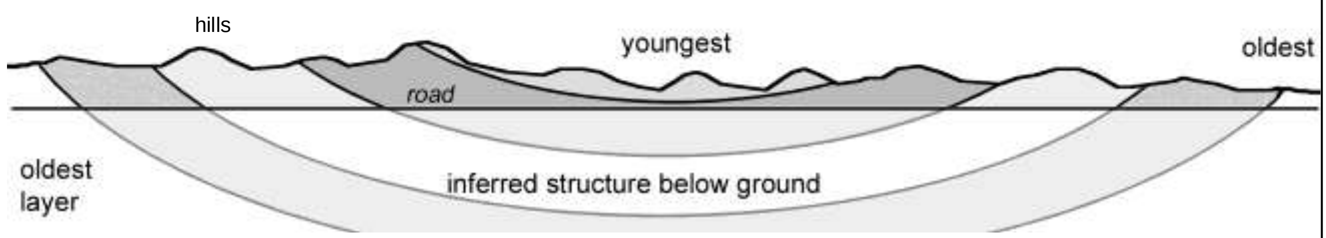


Diagram showing layers of rock folded into a *syncline*. The layers at the surface are seen to be tilted to the horizontal, and the strata are inferred to connect together underground. This is very similar to the section seen in the hills along the banks of the Waikato River heading from Tuakau to Port Waikato; the road runs along the river bank. The horizontal line represents the road, and the layers below the ground have been shown in light grey to indicate that this is an *inference* – we cannot see them directly. The corresponding strata on either side of the fold contain identical fossils, supporting the inference. The distance from left (east) to right (west) is about 20 km.

As well as the simple rule about the layer on the bottom being the oldest (called the “rule of superposition”) some other observations were possible: if a fault cuts across a series of strata, the fault movement is younger than any strata it offsets. If an intrusion cuts across any layers of strata, it is younger than the layers it cuts across.

Using techniques like this, geologists were able to work out the order of formation of very great thicknesses of rock – hundreds of kilometers in places. They found that certain sequences of fossils appeared consitently, and came to use these to give ‘dates’ to particular fossil groups, which they gave names, like “Mesozoic” and “Jurassic” (for parts of what we call the ‘Age of Dinosaurs’).

In the 1800’s they still had no idea how much time was involved. Only in the twentieth century have we developed new techniques, using radioactive minerals, which can date rocks with a high degree of accuracy. We now know, for instance, that the oldest rocks on Earth are about 4,300 million years old, and the Jurassic finished about 135 million years ago. The geological timescale and the time of some important events are shown in the table below:

The Geological Eras

Epoch	Period		Comments	NZ geological history
CENOZOIC 2 my	Quaternary	*Holocene*	Period since end of last glaciation	Sea level and climate changes
		Pleistocene	"Ice ages"	
	Tertiary	*Pliocene*	"Age of Mammals" Ends with a large scale die-off of many large mammals. We now place the beginning of the Quaternary where the first evidence for glaciation occurs.	Renewed tectonic activity 22 my ago, most of NZ emerges from sea
		Miocene		
		Oligocene		50-25 my NZ becomes swampy and sinks below the sea
		Eocene		
65 million years		*Paleocene*		
MESOZOIC	Cretaceous 135 my		"Age of Dinosaurs The boundary between the Cretaceous and Tertiary (called the "K-T boundary") is marked by another mass extinction, covering all the dinosaurs and about $^2/_3$ of other animal and plant species. Mammals first appeared in this era, and after the extinction dominated.	80 my NZ breaks of from Gondwana 110 my NA tectonically quiet 140 my high level of tectonic activity 300-130 my most of NZ greywackes laid down off Gondwana coast
	Jurassic			
250 million years	Triassic			
PALEOZOIC	Permian 299 my		Period of "Old life" (pre-dinosaurs); it begins with emergence of large fossils and land creatures and ends with a mass extinction - 90% of species, including well known fossil species such as trilobites. There are several theories about the cause of this extinction. The extinction paved the way for the evolution of dinosaurs and most of the groups of plants and animals which dominate the modern world.	370 my first emergence of any part of NZ from sea
	Carboniferous			
	Devonian			500-330 my Oldest NZ rocks formed on 'east' coast of Gondwana
	Silurian			
	Ordovician			
542 million years	Cambrian			
Pre-Cambrian			Few major fossils known until 20^{th} Century; most life in this period is single celled or simple with few "hard parts" to make good fossils. We now know that this period covers about $^4/_5$ of Earth's history, from the formation of the Earth to the evolution of complex life and the emergence of life from the sea to the land.	

You do not need to know any of the names or times on this diagram – it is for interest only.

Refer to the diagram on the next page

1. Name the rock units, from oldest to youngest.

Folded rocks, sandstone, granite, mudstone, siltstone, coal, conglomerate

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2. Explain when the granite was intruded and how you know this.

we know that the granite is younger than the sandstone because it intrudes it, but is older than the mudstone because the mudstone 'cuts it off' in an unconformity)

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3. There are two unconformities in the diagram. Explain what an unconformity is, and for one of them, state which rock unit is immediately older and immediately younger than it, and explain how you worked this out.

One between the granite and the mudstone, because the top of the granite is eroded ; the other between the siltstone and the coal because the siltstone is offset by the fault but the coal isn't.

4. Which was the first unit formed **after** the fault moved? How do you know?

The coal, as explained above

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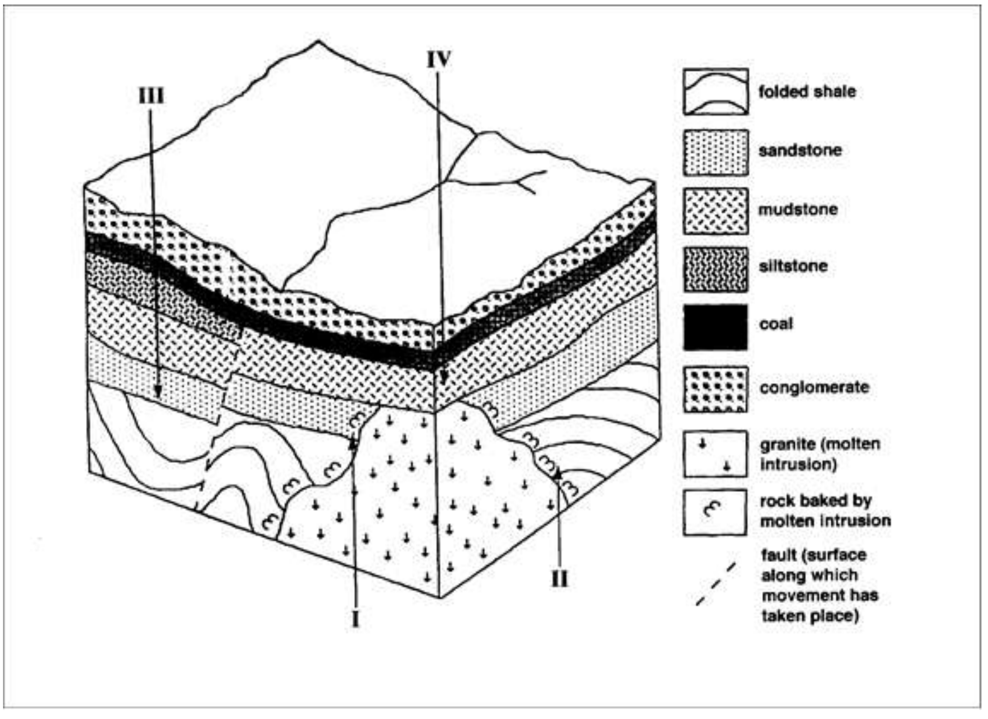


Fossils

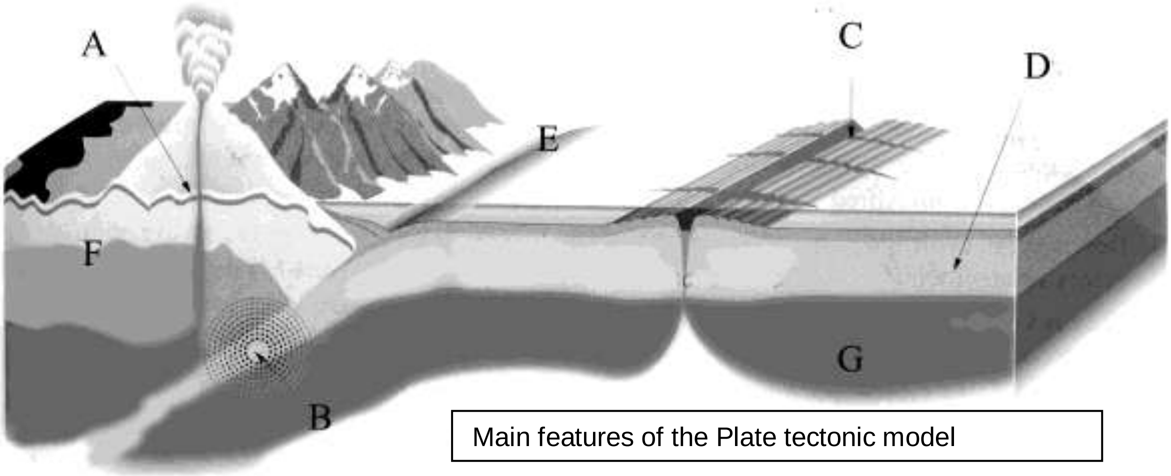
A particular assemblage of fossils can be used to tell what period of time a sedimentary rock has come from. For instance, the greywacke east of Auckland is dated as Jurassic on the basis that a single specimen of the Jurassic mollusk called *Inoceramus*, shown left. This is always characteristic of this era. Fossils can give other information about the rocks in which they are found – for instance, the climate. Fossil coconuts and corals at Muriwai in Miocene sediments tell us that Auckland was warmer 20 million years ago. Similarly, they can give you information about the depth of water or type of environment, such as estuarine or freshwater swamp. This can be valuable in reconstructing past landscapes.

Plate Tectonics

It is assumed here that you already know the basics of this from Year 10 science and this is a review only. A much more detailed explanation of plate tectonics in NZ is required at NCEA level 3.

The processes of the rock cycle have now been incorporated into a model for the crust of the earth known as the **Plate Tectonic Model**. New ocean crust, in the form of basalt lava and related intrusive rocks, is created at a **spreading ridge** or mid-ocean ridge (C on the diagram). As more new ocean floor is created, the older floor moves away from the ridge like a conveyor belt until it is carried back down into the mantle in a **subduction zone** at a convergent **plate boundary**.

Such a plate boundary can be between two oceanic plates, in which case it forms a series of volcanic islands called an **island arc**, or it can be subducted beneath a continent to form a **continental arc.** Both types of arc are marked by a trench (E on the diagram) running parallel to a set of volcanoes (A on the diagram)



Main features of the Plate tectonic model

In a continental arc, the trench tends to get filled up with sediment from the nearby continent. This sediment is too light (low density) to be subducted and so tends to get pushed up onto land, adding to the continent. The same forces also tend to thicken the crust near the plate boundary and the lighter continental crust rises up, causing uplift and erosion. This often exposes rocks from deep down (B) which have been altered by heat and pressure into metamorphic rocks, or even melted to form intrusive rocks.

As the process continues, more and more material is **accreted** onto the edge of the continent. For this reason, continents tend to be older in the middle and younger at the edges. In the case of New Zealand, we broke away from the oldest parts of the continent about 80 million years ago when a new spreading ridge formed towards the edge of Gondwanaland. This ridge was active for 20 million years and formed the Tasman Sea. There was no more subduction close to NZ for about 30 million years, but then about 30 million years ago a new subduction zone was formed, roughly parallel to the Northland peninsular. This subduction zone changed its orientation at some point and is now oriented along a line from Mt Ruapehu to Tonga.

The east coast of the North Island is a very good example of the process of accretion; for instance, if you drive from Taupo to Napier the sedimentary rocks around you gradually get younger, from Jurassic in the Kaimanawa Ranges to Cretaceous, then a break (while we were drifting away from Gondwanaland) and

then from Miocene at inland Hawkes Bay to only about 2 million years old at Bluff Hill in Napier city. These rocks are still being "jacked up" out of the sea – as was shown by the uplift of 2 metres that accompanied the 1931 Napier earthquake – as the process of continental accretion continues today. In a few million years, the sediments presently on the seafloor in Hawkes Bay will also be lifted out of the sea forming a new, younger coastline. At the same time, the mountains inland continue to be worn down to make the sediments that will contribute to these rocks.

While New Zealand continues to lie on a plate boundary, the processes of volcanism and uplift will continue to add land as other areas are worn away. If the plate boundary in NZ ever becomes inactive, we will once again slowly erode down to a series of low lying islands in a shallow sea, as we were during the Oligocene.

3.4 Other Processes

A few other processes need to be mentioned. One of the more important in shaping the landscape we see about us is **sea level change**. The land can rise or fall with respect to the sea, causing features like the raised beaches on the Wellington coast. Sea level itself can change; for example, it tends to fall during periods of glaciation because of the buildup of ice on the continents. The sea level rose and fell a number of times during the Pleistocene for this reason. Changes in the sea floor can also change sea level. An example of this is that sea levels worldwide rose nearly a millimeter after the Boxing Day earthquake and tsunami of 2004 because such a large area of seafloor was uplifted.

Meteor impact has had a pronounced effect at times, by raising large quantities of dust into the atmosphere causing **climate change.** Many scientists think that a meteor impact in Mexico 65 million years ago was the cause of the profound changes that ended the Cretaceous period, though it is possible that other factors contributed.

Climate change can be caused by other factors. The fluctuations that caused the ice ages were caused by variations in the Earth's orbit. But the ice ages could only start after a worldwide cooling caused by geological factors. These included the raising up of mountain ranges (the Rockies and Himalayas) which prevented wind in the northern hemisphere from distributing heat as effectively, and the separation of Antarctica from South America which allowed a cold current to travel right around the southern continent and causing it to freeze over. Other changes occurred with this, in particular much of the world became much drier and forest was replaced by grassland in large parts of Africa.

The majority of scientists think the climate is changing again: warming up. This time the cause is us – returning stored carbon into the atmosphere as carbon dioxide. Understanding geological processes and changes in the past will give some idea of the consequences of this.

1. A single *Inoceramus* fossil was found in greywacke on Ponui Island (near Waiheke Island). What information does this give a geologist?

About the age of the rock; in this case, uppermost Jurassic.

2. On Motutapu Island there are mid-ocean ridge volcanic rocks mixed up with sedimentary rocks. Suggest an explanation for the formation of this sequence.

The Pacific plate was subducting under Gondwana (Australia) 140 my ago. Sediments were deposited in the trench, forming greywacke. Volcanic rocks from the MOR were scraped off the subducting Pacific Plate and mixed in with the greywacke

3. In the Auckland there are three lots of plate boundary volcanoes: in the west, a chain of Egmont-like volcanoes around 20 million years old (Waipoua Forest, the Waitakeres), in the east an area that used to be like Rotorua-Taupo that is now the Coromandel range and is 8-12 million years old. One andesite volcano, Little Barrier, is the youngest at 5 million years. What does this tell you about Auckland?

This suggests that the location of the plate boundary has moved around over time. Subduction was happening below Auckland 20 million to 8 million years ago, but there is no subduction today.

Chapter 2: Rocks

Introduction

Rocks are solid mixtures of minerals (and occasionally other matter such as fossilized plant material - coal). Some rocks will consist almost entirely of one mineral; for instance, both limestone and marble are (by definition) rocks that contain more than 95% of the mineral calcite. Most rocks consist of mixtures or several or many minerals.

It is convenient to try to classify rocks as **igneous, metamorphic** or **sedimentary** depending on how they were formed. The definitions for these three types are:

- **Igneous rocks** are those that have cooled and solidified from a molten (melted liquid) state, either on the surface (volcanic rocks) or deep underground (plutonic rocks).
- **Metamorphic rocks** are those that have changed in their mineral composition and texture as a result of the heat and pressure as they have been buried deep under the ground, but without having melted. The original rock could have been igneous or sedimentary, and usually only an expert could identify which they were.
- **Sedimentary rocks** have formed from fragments of rock, minerals, biological materials such as shells or plant matter and dissolved substances which have been transported to a particular place (e.g. by rivers), deposited as sediment and then formed into solid rock by a process in which the fragments become stuck together.

The diagram below shows the processes which relate the three rock types:

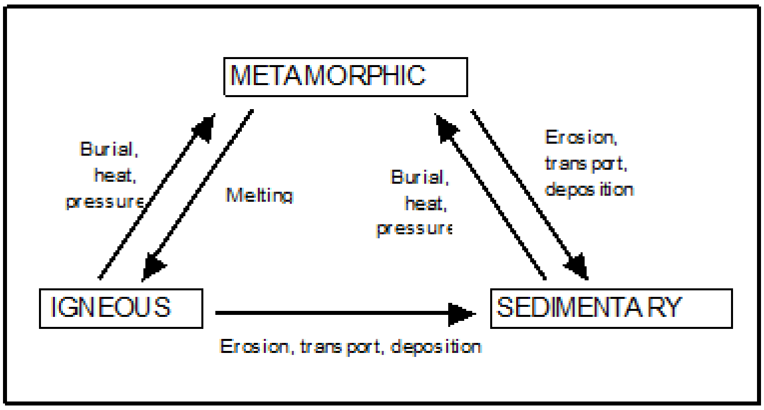


Fig 2.1

The boundaries between the three types are sometimes a bit blurred. This is most noticeable in the transition from sedimentary to metamorphic rocks – there are places where you can trace a particular suite of rocks over the kilometers and see a continuous transition from clearly sedimentary to clearly metamorphic rocks, but nowhere can you put your hand on a rock outcrop and say "This is the place where it becomes metamorphic". Sometimes classification is difficult. Is a recently erupted lahar (mudflow) from Mt Ruapehu igneous or sedimentary? It forms a hard, gritty rock rather like a coarse sandstone, with many of the features of a sedimentary rock, but is composed of mineral fragments that were recently molten. The IMS classification system is useful, but should not be treated as an absolute.

1. Describe the processes that can change

Sedimentary to metamorphic rock: deep burial with enough heat and pressure to change the minerals

Metamorphic to igneous rock: the rock gets partly melted by heat from inside the earth, or heat from a nearby intrusion

Igneous or metamorphic rock to sedimentary rock: the igneous or metamorphic rock is weathered, eroded, transported and buried and is then cemented or lithified (changed into rock)

Igneous Rocks

Igneous rocks have solidified from a molten state that we call **magma**. There are quite a few types of magma, made of different proportions of chemicals and with different minerals. These different magmas have different properties we will look at later.

Some magmas completely liquid, but most contain mineral crystals in a **suspension**. Many people think that the whole of the inside of the earth consists of liquid magma, but in fact the crust and mantle are both more or less solid (though the mantle can undergo a very slow movement called **plastic flow**). However, the lower crust and parts of the mantle are often very close to their melting point and small changes in temperature or other factors, such as the addition of water from crust that gets carried down in subduction, can cause them to partly melt. The liquid produced then moves to become a body of magma. Usually, it is less dense than the surrounding rock and rises towards the surface.

Only a small proportion of this magma reaches the surface to be erupted as **volcanoes** and **volcanic** rocks. Much more remains below the ground, hundreds or thousands of metres, slowly solidifying as it gives up its heat to the surrounding rocks. These underground bodies of magma are called **plutons,** or **intrusions**, and the resulting rocks are termed **plutonic** (or **intrusive).**

You might think that we never see such "deep down" rocks, but in fact they are quite often exposed at the surface by **uplift** and later **erosion** which brings them up and then wears away the overlying rocks. Sometimes you even see these plutonic rocks with the volcano they formed. At Paritu, on the end of the Coromandel Peninsula, you can see the plutonic magma chamber in rocks on the shoreline where the faults that formed the Moehau Range have brought it to the surface. Nearby, behind Colville village, are the remnants of the volcanic rocks that were erupted from this chamber some 10 million years ago when it was about 2 km underground.

Distinguishing features of plutonic and volcanic rocks

Plutonic and volcanic rocks which have been formed from exactly the same magma can show some quite profound differences, even though their chemical composition might be very similar. This is because plutonic rocks have cooled much more slowly, deep underground, and with no opportunity for gas to escape.

The slow cooling means that crystals form much more slowly and therefore will have time to grow much larger. Plutonic rocks also never have the gas bubbles (called **vesicles**) which are common in volcanic rocks, because the high pressure means that gases such as CO_2 and H_2O remain dissolved in the magma and get incorporated into the minerals (note that not all volcanic rocks have vesicles).

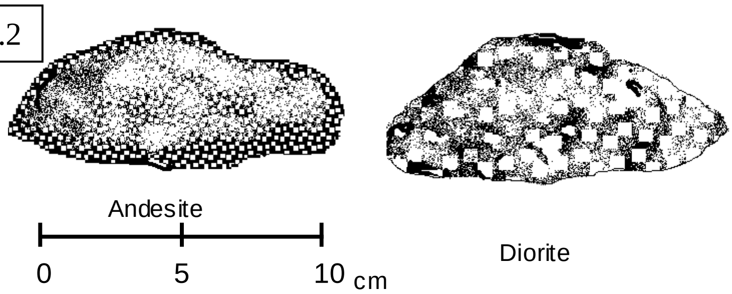
Activity: Plutonic and volcanic

Your teacher will provide a range of igneous rocks. Examine each carefully and see if you can decide whether each is plutonic or volcanic. Try to estimate:

- The average size of crystals
- Whether crystal size is uniform (mostly the same) or bimodal (mostly one size – usually small - but with a few the other size(s) – usually large. This is an indication of a rock that is volcanic. The small crystals are termed *groundmass* and the large crystals *phenocrysts*.
- Whether phenocrysts, if they are present, are all the same sort of mineral or whether there are different types (e.g. some are dark in colour and others are light).
- Whether or not there are vesicles present.
- Whether there is any glass present (this will have no visible crystals and be smooth and *vitreous* in appearance).

Most volcanic magmas have undergone some crystallization underground before they are erupted, resulting in a few large crystals called **phenocrysts** mixed in with the smaller crystals, called **groundmass.** A fine grained volcanic rock with no phenocrysts at all is termed *aphyric*; these rocks are fairly rare and usually indicate very freshly formed magma. The basalts in the Taupo volcanic zone (such as the one from the 1886 Tarawera eruption) have this feature.

Fig 2.2



Andesite and diorite are both formed from the same sort of magma. Andesite is erupted at the surface as volcanoes; diorite cools underground and is later exposed by uplift and erosion. The diorite has larger crystals because of its slow cooling.

Some volcanic rocks cool so quickly they have no time to form any crystals at all after they are erupted. These cool into volcanic glass. Obsidian and pumice (which is just obsidian with lots of bubbles in it, like shaving foam made of lava) are the commonest examples of volcanic glass, and the only crystals you

will find in pumice will be phenocrysts. The term for this rapid cooling is **quenching.** This is most common in silica-rich lavas, which form glass more easily.

Magma

Magma is molten rock. It can be produced by melting of the crust or mantle; normally, this melting is partial so the magma is not chemically identical to the rock that produced it. Different magmas are produced in different places and in different ways.

Basaltic magmas are produced by the dry melting of mantle material, usually through pressure release or heat from mantle plumes. They are mostly formed at mid-ocean ridges, hot spots and rifts.

Andesitic magmas are produced in subduction zones, and probably are caused by reactions between the water released from the subducted lithosphere and the overlying 'mantle wedge', which is termed 'wet melting'. There are several different sorts of andesites produced in different parts of a subduction zone; for example the andesites of Taranaki are different from those of Tongariro (they overly a deeper part of the subduction zone). The island andesites e.g. Raoul Island are different again. This suggests that the processes that produce magma from subduction are quite complex.

Rhyolitic magmas are produced by the melting of crustal rock, or mixing of crust and basalt to andesite magma, or when andesite magmas are modified by partial crystallization. They are mostly found in continental arcs and back-arc rift zones, although large island arc volcanoes (such as some underwater ones in the Kermadecs) can produce rhyolite. A rock called dacite is in-between rhyolite and andesite. Current thinking weems to be that most rhyolites in the TVZ are produced by crustal melting by and partial mixing with large volumes of basalt magma produced by the back-arc rift process. Most of this basalt does not make its way to the surface (the 1886 Tarawera eruption was produced by some that did).

Magma composition and rock type

There are many ways in which the composition of magma can vary, but the most important is the amount of silica (SiO_2, or molten quartz) dissolved in the magma. The way that this shows up in the rock is the proportion of light coloured (white, cream, pink) minerals, which are compounds of silica and aluminium, calcium, sodium and potassium oxides. Dark (black, brown or green) looking minerals are compounds of silica and iron or magnesium oxide, and contain much less silica. So the more light coloured minerals there are in a rock, the more silica-rich it is. Rocks with a high proportion of dark minerals are silica-poor. Rocks in between are termed intermediate. Volcanic and plutonic rocks can be roughly named according to the proportion of silica present in the magma:

Silica content	Low silica (45-55%):	Intermediate (55% - 64%)	High silica intermediate (65%-70%)	High silica (>70%):
Volcanic rock name	basalt,	andesite,	dacite,	rhyolite,
Plutonic rock name	gabbro.	diorite	granodiorite	granite

Note: the term dacite was not used in the NCEA exam, but several well known volcanoes in NZ have this lava type including Mt Maunganui, Mt Edgecumbe and White Island. Dacite volcanoes, as the composition implies, tend to be somewhat between andesite and rhyolite in their appearance and eruptive style.

Special igneous rock types:

Basalt or andesite lavas which are full of bubbles are termed **scoria**.
Dacite or rhyolite lava full of bubbles is termed **pumice**.
Obsidian can be formed from volcanic glass of andesite to rhyolite composition (rhyolitic ones are most common). Pumice is obsidian that is full of bubbles. A mixture of pumice and ash deposited by pyroclastic flow is termed ignimbrite. Glass with a low silica composition (often found in scoria) is called tachylite but is often not very glassy looking. Glass forms when lava cools too quickly to crystallize (this is called *quenching*).

Types of Volcano

Magma which reaches the surface is erupted to form a volcano. It then cools quite quickly to form fine-grained volcanic rock. The different appearance of different volcanoes depends mostly on four factors: the viscosity (runniness) of the magma, the amount of dissolved gas (mostly H_2O and CO), whether or not the magma encountered groundwater on its way up (hot magma tends to explode when it encounters liquid water, particularly if this happens just under the surface), and how much (volume) of magma was erupted.
As the magma reaches the surface, gas that is dissolved in it begins to form bubbles due to the pressure release. This is very similar to the way that bubbles form in soft drink when you open the bottle. Before the bottle is opened, the gas is kept dissolved by a combination of pressure and chemical reactions:

$$H_2CO_{3\ (aqueous)} \text{<--->} H_20_{\ (liquid)} + CO_{2\ (gas)}$$

aqueous carbonic acid <---> liquid water + carbon dioxide gas
(reversible reaction, pressure dependent)

When the bottle is opened, the equilibrium moves to the right. If it is vigorous enough, the drink can spray out (in the coke/mentos photo on the right, the reaction has been sped up by a catalytic effect of the mint through a phenomenon called nucleation)

When magma approaches the surface, a similar reaction occurs:

$$H_4SiO_{4\ (molten)} \text{<--->} SiO_{2\ (molten\ silicates)} + 2H_2O_{\ (gas)}$$

molten silicic acid <---> silcate melt + steam
(reversible reaction, pressure dependent)

Note that other chemical reactions in the magma contribute to the water pressure; in some ways it can be considered an acid-base reaction e.g.

$$MgO + FeO + H_4SiO_4 \rightarrow FeMgSiO_4 + 2H_2O$$

The compound $FeMgSiO_4$ is the mineral **olivine**; it is crystalline, so forms as the magma cools. It is denser than the melt and settles to the bottom of the magma chamber. This alters the composition of the magma. There are many other similar but more complex reactions, which ones take place depends on the magma composition.
The net effect is that as magma approaches the surface, steam and other bubbles of gas are created.. This can result in vigorous explosions or fountains of lava.
Remember: The more silica-rich a magma, the less runny (or more viscous) it will be.

Imagine if in the mentos photo the consistency of the coke something like golden syrup and the pressure even higher. It couldn't possibly escape fast enough from the bottle (too viscous) so would explode instead of fountaining out. If it was hot hokey pokey with the bicarb added, and it solidified into blobs as it sprayed out, you would have a model for the formation of pumice.

Other gases besides water are significant in volcanoes, particularly carbon dioxide, hydrogen sulfide and sulfur dioxide. Some of them are also kept in pressure solution.

A large amount of the variation in volcanic activity is due to how much dissolved gas there is in the magma and how easily it can escape.

(note: there is an exception; magma very rich in sodium or potassium can be anomalously fluid. Mayor Island is a NZ example of such a lava - it is rhyolite, but unusually fluid and the eruptions are more like basalt).

The most fluid magmas flow a long way over gentle slopes and the gas escapes easily, so they tend not to be very explosive. Very 'sticky' magmas tend to be shattered into little bits as the gas tries to escape; this causes explosive and ash eruptions. Blobs of this lava can actually expand with bubbles as they fly through the air to form pumice. Viscous but gas poor lava flows form steep cones or domes.

2. Which type of magma is most fluid and which type is most viscous?
Basalt is most fluid; rhyolite is most viscous

3. Why do gas-rich and viscous magmas tend to explode?
Because the gas bubbles can't escape fast enough

4. What are the main gases found in volcanoes and how do they form?
Water vapour (steam), from dehydration of silicic acid (water dissolved in the magma)
Carbon dioxide and sulfur dioxide, dissolved in the magma

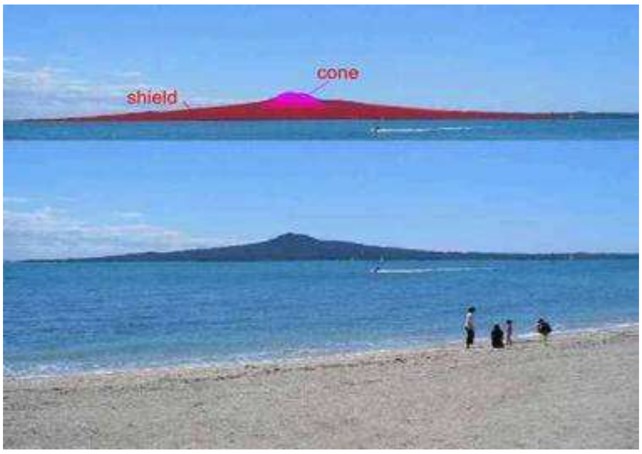
Basalt volcanoes

Basalt magmas are quite runny, so the gas can escape quite easily (often producing a fountain of lava) and the lava flows long distances over quite gentle slopes to form a “shield” shaped volcano. Some of the frothy magma sometimes solidifies near the fire fountain before it can flow away, so it builds up a steep but small cone of scoria. Mt Wellington is a good example of such a cone. The scoria tends to float on top of lava like soapsuds on water. These cones are called scoria cones (in NZ) or cinder cones (note that they often, but not always, have a central crater; if they don't they can be mistaken for rhyolite domes but they are much smaller than such domes). Some NZ cinder cones sit atop shields e.g. Rangitoto, One Tree Hill. Others form small, discrete volcanoes (which is the more common form overseas).

Explosive activity often occurs at the beginning of the eruption when the hot magma encounters rock and soil wet from groundwater; this is referred to as a phreatic eruption. If the volcano splutters to a halt after this, you will be left with a large, shallow explosion crater surrounded by a shallow ring-cone of the ejected material (called tuff).Otherwise, a scoria cone will build up in the centre, as shown in the photo below of a volcano on the margins of Lake Omapere, Northland.

Tuff ring and scoria cone, at the dege of Lake Omapere. Tuff has been coloured pink for recognition.

Tuff layers, North Head, Auckland



Rangitoto, shield volcano with summit cone

Explosion craters of this sort are called maars; Panmure Basin, Orakei and Onepoto are all examples in the Auckand field and there are numerous others in the Auckland and Franklin fields. They are not well preserved over long periods of time, so tend to be found in young fields. Some literature wrongly labels maars as calderas. One way to tell the difference is that calderas are much larger (explosion craters are rarely more than about 2km across). See the picture of Lake Rotorua down the page for an example.


Mt Wellington from Taylor hill, now... ...and as it might have looked 9000 years ago

Many volcanoes then build up some small cones (scoria cone or cinder cone) inside this explosion crater, and some completely overwhelm their explosion crater and bury it in lava, e.g. Mt Wellington (above). These largest of the basalt volcanoes are the ones that build up shield volcanoes. Only Rangitoto and One Tree Hill, in Auckland, show clear shields in NZ. Mt Wellington formed a lava 'lake' which was quarried and the hole left behind is being subdivided into housing.


Aa lava surface, Rangitoto Pahoehoe lava cliff, Milford

Although basalt lava is very fluid, it can form different textures on the surface. The blocky surface at Rangitoto on the left is a texture called aa (pronounced like 'haha' without the h sounds), or it can form a smoother surface called pahoehoe. The pahoehoe above right has formed a skin of solid rock while still liquid lava drained out underneath, you can see that just below the top of the photo. When this happens more extensively it forms caves called lava tubes or lava caves. I have a video clip on this but have removed it from the page because it was causing it to crash. contact the author if your are wanting to use video resource material.

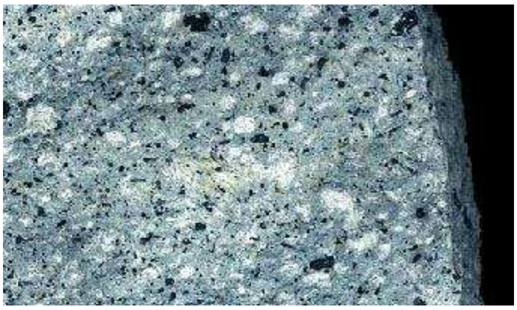
5. Why do basalt volcanoes often form shallow-sloped 'shield' shapes?
The lava is very runny and can flow over gentle slopes
6. Under what circumstances do basalt volcanoes become explosive?
When they encounter water e.g. hit groundwater on the way to the surface. It forms an explosion crater maar e.g. Panmure basin
7. Explain the following terms:
Tuff: layered ash from the explosive surges around a basalt vent

Scoria basalt full of bubbles (foamed basalt); formed during the fire-fountaining stage of a basalt or andesite eruption
Pahoehoe: basalt lava flows with a ropy looking surface
Aa: basalt lava flows with a blocky, rough surface; formed when there is a solid crust on the flow which is constantly broken up and moved by the flowing lava

Intermediate volcanoes - andesite

Intermediate magmas are less runny, and form large, steep lava cones. Mt Egmont/Taranaki and Mt Ngaruahoe are good examples of this; Mt Ruapehu is also an example but consists of several cones grown together.

Taranaki



Andesite

Taranaki is an andesite cone, with a small 'parasite' cone (a second but less active vent from the same magma source) inturrupting its otherwise very symmetrical shape. The close up shows andesite similar to that from Taranaki/Mt Egmont. Lower silica intermediate volcanoes have scoria on them, rather like basalt volcanoes. Ngauruhoe is a very low silica andesite. Its slopes are loose scoria.

The Waitakere Ranges in Auckland are the remains of the eastern flank of an Egmont-sized volcano which was a volcanic island 20 million years ago. 90% of it is eroded away, but the resistant rock forms hills to the west of the city. Lahars from this volcano flowed into the sea (or started underwater) and are found interbedded with the sedimentary rocks around Auckland, where they are known as the **Parnell Grit** after their type location behind the Parnell Baths.

Mt Edgecumbe

Tauhara

High silica intermediate: These volcanoes are a bit steeper than normal andesite volcanoes, in-between cones and domes. Edgecumbe and Tauhara are two examples. The rock type is called dacite. They are intermediate rocks with 65-69% silica. Quite a few of the underwater volcanoes between White Island and

Tonga have this composition. One of the main distinguishing characteristics is that when full of bubbles the lava is more like pumice than like scoria. There are outcrops of dacite around the Cascades area in the Waitakeres.

1. Explain the following terms:

Stratovolcano: cone shaped andesite volcano made of layers of ash and lava e.g. Taranaki

Lahar: a mudflow of volcanic ash and rocks, about the consistency of wet concrete

Andesite: an intermediate volcanic rock usually found at convergent plate boundaries

Dacite: a higher silica intermediate rock that forms steep cones; also found at convergent boundaries

2. Why are the Waitakeres not a cone?

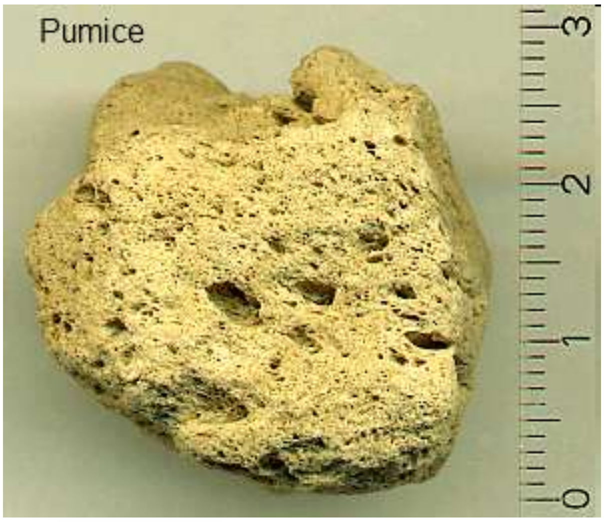
The original cone is eroded away. The present hills are the lower eastern flanks of a volcano that was at least as big as Taranaki and mostly underwater.

3. Andesite volcanoes are a sign of an active plate boundary. When was there a plate boundary close to Auckland and where was it?

15-20 my ago the plate boundary ran parallel with the Northland Peninsula from Coromandel up to Whangaroa. Volcanoes were the Waitakeres, Kaipara, Waipoua, Mangawhai Heads, Hen and Chicken Islands, Whangarei Heads and elsewhere.

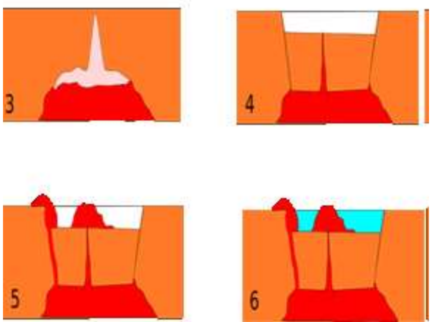
Rhyolite

Rhyolite is made from a very silica-rich type of magma. If it cools underground, it forms granite. Silica-rich magmas are normally very viscous, and as a result the gas has great difficulty escaping. Their eruption mode therefore depends on how much gas is present.



Pumice formation: gas-rich rhyolite magma is 'blasted out' as blobs of thick, syrupy lava. As these fly through the air, they rapidly expand (like unexpanded polystyrene dropped in hot water, or when you put the bicarb in while making hokey-pokey). These bubble-filled glassy blobs make pumice. Pumice is volcanic glass with bubbles (mostly formed by water vapour). It is usually rhyolitic in composition, but some pumices are dacite (particularly those from the offshore volcanoes between White Island and the Kermadecs). Pumice may contain some crystals that were in suspension before eruption (called phenocrysts).

Caldera formation: many NZ rhyolitic eruption centres are so large that they form calderas. It is important to understand that

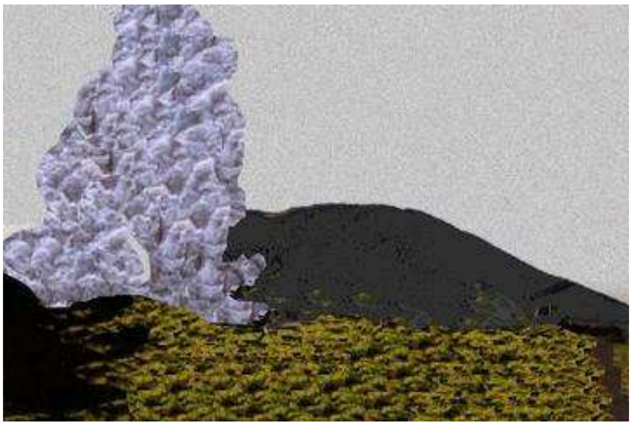


this is not a crater. It is formed by ground subsidence. So much magma is erupted that the overlying ground subsides, forming a depression called a caldera (to see a picture of a caldera on the summit of the underwater Brothers volcano, click here).

Below right is a Google Earth view of the Rotorua Caldera, looking towards the west from above Lake Okataina. You can contrast the size of Lake Rotorua with the explosion crater in which Lake Rotokawau is located (near Hell's Gate, lower right of picture). Despite this huge size difference, the Rotorua caldera is one of the smaller calderas in the TVZ (and Lake Rotokawau a fairly large explosion crater). Above right is a diagram showing the stages in the formation of a caldera. One of the features to note is the formation of a dome, often over the vent. Mokoia Island is an example of such a dome, as is Mt Ngongataha and Hospital Hill in Rotorua. In the extreme foreground are some of the domes at the edge of the much larger Okataina Volcanic Centre.

Pyroclastic flow: The hot material can be carried high by the expanding, lighter-than-air superheated gas (mostly water vapour). Eventually, this eruption column loses buoyancy and collapses. The resulting materail hits the ground at high speed. It is still very hot - 300 to 600 degrees celsius. The turbulence when it hits the ground sucks in cold air, which rapidly expands, creating more turbulence, which sucks in more air and so on. This creates a turbulent cloud of hot ash which can flow tens of kilometres over the ground at high speeds (100 to 400 kph) in a pyroclastic flow. It will continue until it is no longer fast enough, or hot enough, to create the turbulence that keeps it going (further from the vent, pyroclastic flows often become confined to valleys as the downhill movement helps keep up the speed).

Large pyroclastic flows leave behind a layer of distinctive ash called ignimbrite. Some of these ignimbrites are tens of metres thick, extending for hundreds of square kilometres. In quite a few of them, the pumice and glass shards of the ash were so hot when the ignimbrite formed that they have welded together to form a hard rock very much like the rhyolite you find in a dome (see next section). The photo on the right is of such an ignimbrite outcrop in the Waikato (known locally as Hinuera Stone). Such rocks puzzled geologists in the 19th Century because they knew this lava was too viscous to form the large, flat sheets they found; it was the 1930s before the explanation was forthcoming. The youngest ignimbrite in the North Island is the Taupo Ignimbrite, erupted about 230 AD from a vent near the east side of Lake Taupo. It is a non-welded ignimbrite and is relatively thin because it was moving much faster than average.



Maungaongaonga dome... ....with a small pyroclastic flow on the east flank

Small dome near Tokaanu (southern end of Lake Taupo)

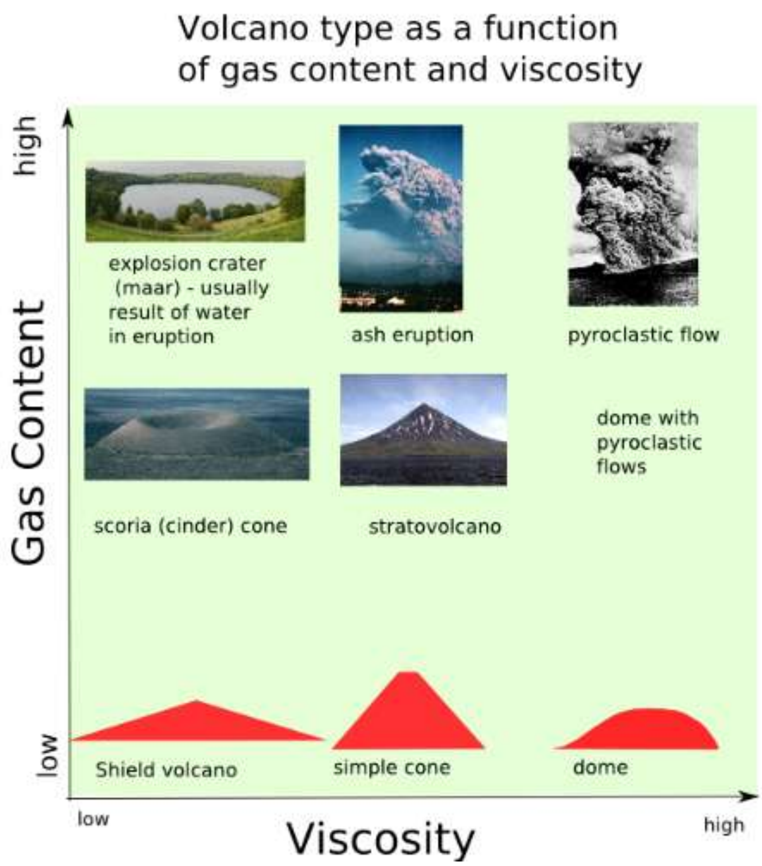
Dome formation: Once the caldera has collapsed into the partly empty magma chamber (3 and 4 in diagram), some magma is usually erupted out the vent and the caldera margin faults to form rhyolite domes (5 on the diagram). This magma has lost most of its gas, so 'oozes' out relatively quetly. Domes can form pyroclastic flows when the hot rock on their steep side collapses and disintegrates, sucking in cold air in a similar manner to the very large events; however, these pyroclastic flows are usually small and only travel a few hundred metres beyond the foot of the dome. There are over a hundred rhyolite domes in the Rotorua-Taupo area. The skin of the dome is sometimes quenched, forming obsidian (quenching means very rapid cooling; no crystals form and instead it forms glass), while the inside is made of rhyolite.The rhyolite dome in the photo on the right is on the southside of Lake Taupo, near Tokaanu. The dome shape is clearly visible. It is partly buried in the fan of sediments where the Tongariro River enters the lake, so what we se here is the emerging top of the dome. The dome in the photos above (Maungaongaonga, near the Waikite Valley) is more typical. I have shown a possible recreation of the emplacement of the pyroclastic debris flow that can be seen on the left looking at the hill might have looked like. The present flat area in the foreground is the floor of a former lake.

There was active rhyolite volcanism in the Coromandel area, Great Barrier Island and to the north of Auckland around Mangawhai heads at the same time the Waitemata sedimentary rocks were being formed. Ash from these volcanoes contributed to the sediment.

Lakes: Calderas often then fills with water, forming a lake (6 on diagram), or several lakes (Lakes Okataina, Tarawera and Okareka all lie within a single caldera/volcanic complex called the Okataina Volcanic Centre).Lake Rotorua is a good example of such a caldera. Mokoia Island is a dome in the caldera centre, and there are quite a few other domes around the caldera including Ngongataha and Hospital Hill.

Summary: The diagram right summarizes the relation ship between viscosity and gas content in forming different sorts of volcanoes. It shows gas content increasing upwards on the vertical axis, and viscosity increasing to the right on the horizontal.

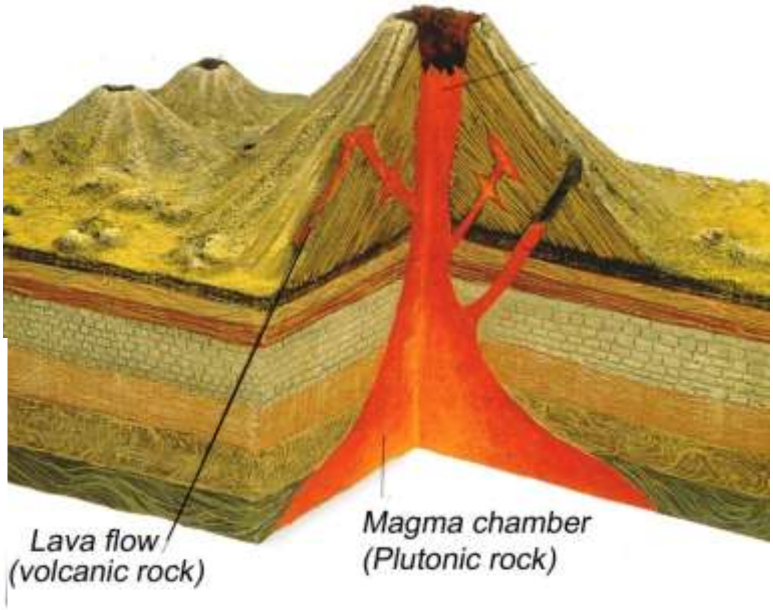
Of course, real volcanoes don't look at this diagram when they erupt, and many volcanoes will have a mix of different eruption types. Neither are the boundaries between the types sharp - different sorts of volcano grade into each other.

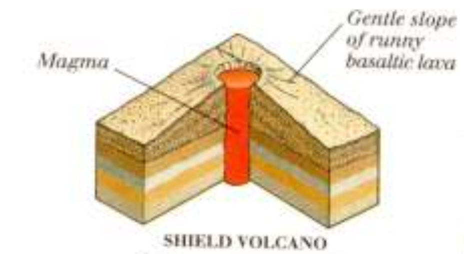


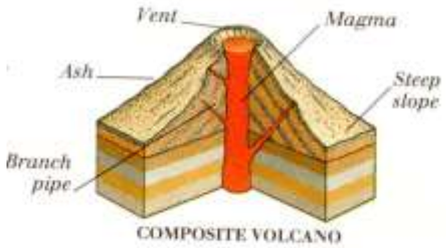
picture from: Cox, G: Fountains of Fire (Collins 1989)

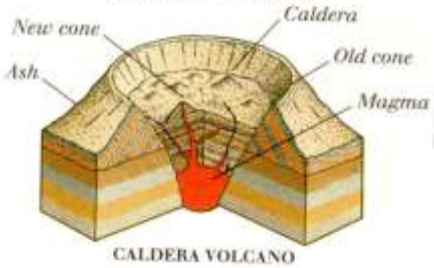
Fig 2.5: This shows how Mt Taylor might have looked as it erupted, looking towards the Pompallier block from Mt Taylor drive. The outer ring of ash was formed by an explosion when the hot magma encountered a stream valley running through what is now Crossfield Park. The magma which cooled and hardened while still full of bubbles formed the cone of the hill, and the runny lava flowed away towards Glendowie College.

Fig 2.6: Cross section through a volcano (not to scale). In practice, the main magma chamber would be a lot deeper underground than this









Pictures from: Dorling-Kindersley Science Encyclopedia; slightly modified

Mokoia Island in Lake Rotorua is a rhyolite dome volcano sitting in the middle of a caldera.

Fig 2.7: Some types of volcano

Activity: Sugar Magma

Molten sugar is very similar in its behaviour to magma. It can vary in viscosity (mostly with temperature), and when it is "quenched" by rapid cooling it forms a glass (in this case, an edible one. The term "glass" refers to a liquid that has solidified without forming crystals). To form a "sugar magma" you add sugar to golden syrup at the rate of about 2 parts of sugar to 5 of golden syrup, and you heat it. This makes the sugar dissolve in the golden syrup to form a mixture that would be solid at room temperature.

- If you don't fully dissolve the sugar, you get sugar "phenocrysts" in the syrup "magma". This may mean that there is too much water left in the golden syrup and your "sugar lava" would be chewy with crunchy bits rather than fully crunchy.
- If you cool it down slowly enough, it will crystallize. This makes sugar lumps.
- If you rapidly cool it, e.g. tipping the "sugar magma" onto a cold plate, you will get "sugar glass". This is how sweets like barley sugars are made.
- If you add a bit of baking soda, this imitates the effect of gas in the magma. The "sugar magma" will rapidly expand (if you could imagine doing this in a full bottle so that the expanding "sugar magma" squirted out the top, you would have a good model of how a volcano works). If you keep heating it the gas bubbles will escape, but if you tip the frothy "sugar magma" out onto a cold plate it will set into sugar glass full of bubbles – hokey pokey. This is the "sugar magma" version of pumice.

1. There is a pyroclastic flow deposit near St Kentigern College that originated from the Mangakino Volcanic Centre, near Taupo. How did the volcanic material get so far? ....

Transport as pyroclastic flow – a mix of hot gases and pumice and ash, travelling at hundreds of kilometres per hour along the ground

2. Caldera volcanoes often produce geothermal activity which deposits minerals such as gold under the ground. Why was Great Barrier considered for gold exploration?

It was the site of a caldera about 12 million years ago

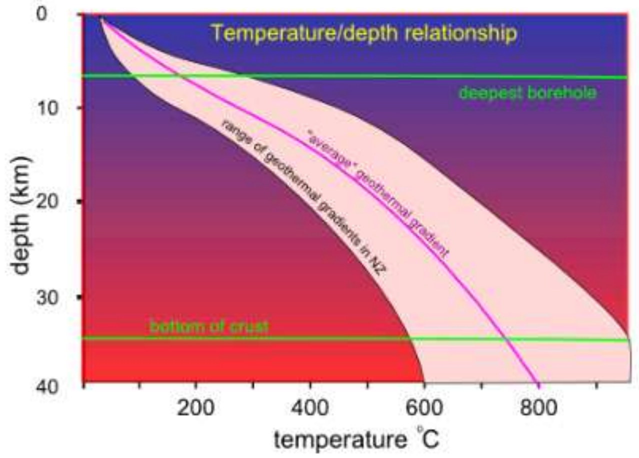
3. You can't see any domes around Coromandel any more, and the calderas in the area are very difficult to detect. Why?

They have eroded away or been covered up by younger stuff. The "pinnacles" are their remains

Metamorphic Rocks

These are rocks whose mineral composition and/or texture, have been changed as a result of heat, or a combination of heat and pressure

Heat and pressure in the crust



Most people know that the earth gets hotter the deeper down you go. The deepest boreholes in NZ only go to a depth of about 5 km, but measurements in them confirm the temperatures worked out by calculations from theory. So, although we can't directly measure the temperature at depths much more than 5 km, the fact that the temperature rise over the first 5 km agrees with the ones calculated suggests that the calculations for greater depth should be accurate. The rise in temperature with depth is called the **geothermal gradient.**

The average geothermal gradient in NZ is about 30°C per km. The non-volcanic hot springs, such as those on the East Coast north of Gisborne or Hanmer Springs in the South Island, are warm because water from great depths rises up fault lines too rapidly to cool all the way back to normal temperatures. Laboratory experiments suggest that new minerals start to form at temperatures of around 200°C, which translates to a depth of around 7 km.

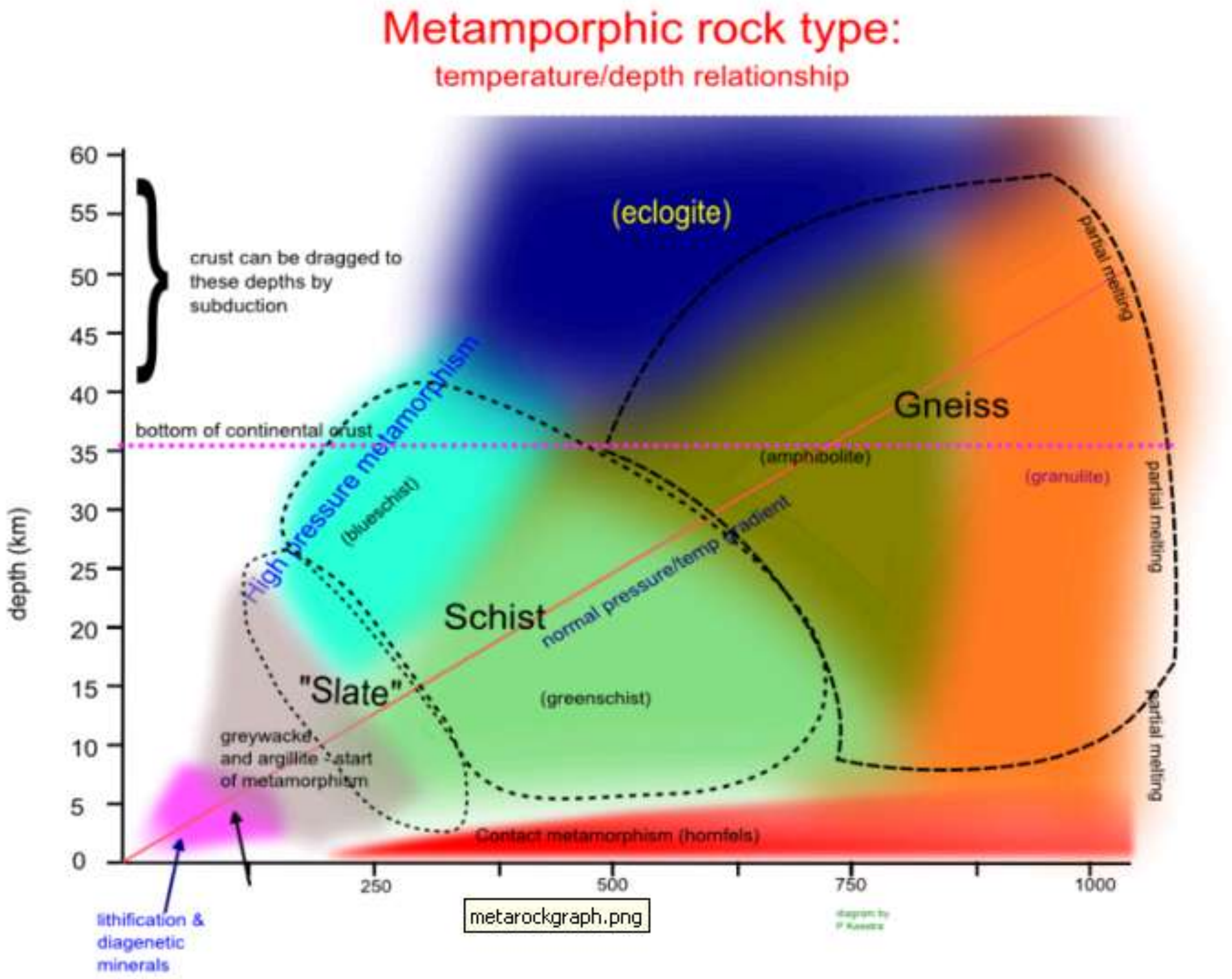
Hanmer Springs. The waters rise up a fault line and are heated by the natural geothermal gradient.

Pressure is caused by the weight of the column of rock directly overhead, so you can work it out if you know the density of the rock. At a depth of 10 metres underground the pressure is about 30 times that of the air around you. One kilometre down it is about 3000 times atmospheric pressure. So at the depth where rocks begin to metamorphose, the pressure is tens of thousands of times atmospheric pressure. An increase of 30°C and 3000 atmospheres per km depth is called a **normal P-T gradient.** Rocks that undergo metamorphism due to this normal increase in pressure and temperature are said to have undergone **regional metamorphism.**

If there is an igneous intrusion nearby the geothermal gradient around it will be unusually high. The rocks metamorphosed by this undergo a type of metamorphism called **contact metamorphism**, with high temperature and low pressure. The intrusion at Paritu, on the end of the Coromandel Peninsula, has contact metamorphosed the sedimentary rocks around it. Contact metamorphism is fairly localized.

Sometimes rocks get dragged down in a subduction zone without strong heating. These are **high pressure metamorphic** rocks. The nearest place to NZ where they occur is in New Caledonia, and the rocks produced are known as blueschists and eclogites.

Different sorts of metamorphic rocks are formed at different pressures and temperatures. The relationship of metamorphic rock type to temperature and depth is shown in figure 2.8:



Slate, schist and gneiss are rocks distinguished mostly by their texture. Geologists base their classification of metamorphic rocks on a more detailed description of the new minerals formed, using terms such as “greenschist” or “amphibolite” or more specific terms.

<u>Metamorphic rocks in NZ</u>

Most of the main ranges of both the North and South Islands are made of rocks called **greywacke** and **argillite**. Greywacke is a sandstone, and argillite a mudstone, right on the border between being sedimentary and metamorphic. In most places, some of the features of the original sedimentary rock are still visible so many geologists do not consider them truly metamorphic. They do contain some new minerals. In places the argillite is slate-like in appearance. Near the Alpine fault, the sediments that formed these rocks have been uplifted much further in the past and we see rocks from deeper down. These form the **schist** of Otago and elsewhere in the South Island. In places, particularly around Fiordland, there is gneiss from deeper still.

<u>Some types of metamorphic rock</u>

Slate is a fine-grained mud or siltstone that has just begun to be metamorphosed. It breaks into thin, flat sheets that were once used for writing on and making rooves. In NZ, these rocks are often too shattered and mixed up to form good slate and more commonly form argillite. A characteristic of slate is that when you scratch a piece of slate with another piece it leaves a white mark.

Schist is a layered metamorphic rock similar to slate, but with larger crystals. You can see the shiny crystals of the mineral mica on the surface. It has been buried deeper than slate, and often minerals have separated into layers. Most NZ schist is termed “greenschist”, and is often (but not always) greenish in colour because of the presence of the minerals chlorite and epidote. A decorative purple schist often used as a building stone is formed from metamorphosed manganese–bearing rocks that are common in the greywacke sedimentary rocks; once they were manganese nodules on the sea-floor.

Gneiss tends to lack the layered structure of schist. Mineral grains can be up to several cm in size, with large mica crystals featuring prominently.

Marble is metamorphosed limestone. Because limestone recrystallizes so easily, it can be a bit difficult to tell whether a very white limestone is truly a marble or just a crystalline limestone unless it has the characteristic “marbled” appearance, caused by metamorphic minerals. The only marble in NZ is the Takaka/Mt Arthur marble found in and around Abel Tasman National Park. It is a sturdy building stone and is often a grey colour because of graphite impurities . The Mt Arthur marble is the thickest carbonate rock formation in the country and contains the largest and deepest cave systems.

Activity: Metamorphic Rocks

Your teacher will supply you with a range of metamorphic rocks. See if you can decide whether they are slate, schist, gneiss or marble based on the features described above.

Sacred Heart Church in Takaka is built from Takaka Marble. Note the grey colour, due to graphite in the marble from metamorphosed coal fragments, originally plant material. Above left is Harwood’s Hole, a famous tomo in the marble in Abel Tasman National Park.

1. Briefly describe how temperature and pressure are related to depth. ....

Temperature increases about 25 degrees per km, and pressure increases about 1 atmosphere per 3 m

2. Define the term “metamorphism” and describe what changes happen in rocks when they undergo metamorphism.

Metamorphism is a change in the mineral composition due to heat and pressure; it is often accompanied by a change in texture and visible new minerals such as mica.

3. The basement rock in Auckland is greywacke, a rock on the border between sedimentary and metamorphic. Use the diagram to work out how deeply it has been buried. Why is it now at the surface in places (e.g. the Hunua Ranges)?

About 10 km. This means that this much rock has been removed by erosion (this mostly happened in the Rangitata Orogeny, 130-110 million years ago). The Hunua Ranges have been created by recent uplift and removal, by erosion, of younger rocks.

2.4 Sedimentary Rocks

Sedimentary rocks are formed from grains of minerals and rocks, dissolved minerals and other material, such as plant matter or animal remains, which have been transported and deposited as sediment. After deposition, as the sediments become buried deeper and deeper, they become transformed into rock by a process called **lithification** (or **diagenesis)**.

Coal seam in sandstones at Kaka Point, Southland. Such coal-bearing strata are

Origins of sedimentary materials

Most materials that are incorporated into sedimentary rock are derived from the processes of **weathering** and **erosion,** during which solid rock is broken down into smaller fragments. Volcanic debris can also be incorporated into sediments fairly directly, either through the fall of ash over a wide area, or through transport of volcanic fragments (for instance, when a volcanic cone or island becomes unstable and collapses). In most cases, the resulting rock has been formed by transport and deposition and is therefore classed as sedimentary. The volcanic grits found interbedded with the sandstones and mudstones in the cliffs around Auckland are an example of this.

Material of biological origin is also significant in sedimentary rocks.

Close up of limestone texture, Punakaiki, showing detail of flaggy structure.

Plant material can be found as fragments in sandstones or other sedimentary rocks, and if it makes up the bulk of the rock it is termed **coal**. The shells of many marine organisms are made of calcium carbonate, and form **limestone** or calcite-rich sediments such as **marl** (a **calcareous** mudstone). These shells can include bivalves, microscopic shelled plankton and corals. Other organisms make their shells from silica (SiO_2), and their shells compact into a hard form of sedimentary quartz called **chert** and **flint.** The remains of the soft parts (living tissue) of various organisms is also sometimes incorporated into the sedimentary rock to form **oil shale**. The oil and gas is often squeezed out of these rocks by heat and pressure to escape at the surface as gas seeps or be trapped underground in oil or gas fields. Dissolved minerals can be important in some sedimentary rocks. Calcite is the most common, but dolomite and limonite (a form of hydrated iron oxide), siderite and barite are others that occur quite often.

Limestone outcrop with small cave, Port Waikato. This type of layered limestone is called “flaggy limestone” because it resembles flagstones; the flagginess is caused by layers weathering at slightly different rates.

Mineral grains often survive several cycles of erosion and deposition, so a sedimentary rock can be formed from material that was eroded from other sedimentary rocks. These “second generation” sedimentary rocks are often very rich in clay minerals (because more and more of the feldspar minerals will break down into clay over time), and mineral grains are often stained and very worn down and rounded. By contrast, a sedimentary rock formed from fresh volcanic ash will contain large numbers of grains which are clean, shiny and angular.

<u>Transport</u>

There are four main transport mechanisms for sediment.

- By water (stream, river, underwater currents)
- By wind/air (wind blown sand and dust)
- By mass movement (landslide, rockfall, volcanic cone collapse etc.)
- By ice (glaciers acting as “bulldozers”, or “dropstones” – stones dropped out of icebergs as they melt)

Water

This is by far the most important transport mechanism. Streams and rivers can carry sediment a long way. A “muddy looking” river like the Wanganui will be carrying large amounts of sediment in suspension. More sediment moves along the river bed, particularly when it is in flood. Another important and less well known mechanism in water is the **turbidity current** (or **density current)**. This is an underwater “river” of sediment-bearing (or “**turbid”**) water flowing across the sea bed. The turbid water is denser than the normal water, and can flow tens of kilometres underwater at several kilometres per hour. Turbidity currents usually originate when the “pile” of sediment dumped near a river mouth by the slowing water becomes unstable and collapses. Because the sediment pile eventually builds up again, sedimentary strata formed by turbidity currents tend to consist of thick layers of sandstone or coarser sediment (formed by a single turbidity current event) alternated with thinner layers of very fine sediment (mudstone or siltstone) that was carried out to sea in suspension. The cliffs

Fig. 2.6: Turbidity current deposits, Takapuna beach. The bands of sandstone stand out, while the mudstone layers between erode away faster.

around Auckland are a good example of these **turbidites** (also called “flysch” or “papa”), and the main greywacke ranges of both the North and South Island are composed of them.
A characteristic of water-born sediments is that the particle size often decreases the further the sediment has been transported. In many cases, fragments become less angular and sharp the further they are transported, because sharp corners get knocked off as the particles tumble over each other.

Wind (Aeolian deposits)

Sand dunes, north Hokianga

The best known examples of these are the dunes of a beach or desert. The Awhitu Peninsula, on the western side of the Manukau Harbour, is formed from many layers of dunes emplaced during periods of different sea level. Another important wind formed deposit is called loess. This is wind-blown dust, often “rock-flour” formed when glaciers grind their way over hard rock. There are significant deposits of loess in the South Island.

Mass movement
This is a general term for landslides and other related phenomena. It can be locally important; much of the “ring-plain” of Taranaki was formed by gigantic rock-avalanches that occurred when the volcanic cones got too big and became unstable. There are similar deposits mixed with the sandstones and mudstones around Auckland; either the avalanches entered the water or occurred underwater. West Tamaki Head, near St Heliers, is formed from such a deposit. Twenty million years ago, when these rocks were laid down, there were a number of volcanic islands to the west and north of Auckland (the Waitakeres and at Dargaville).

The viaduct in Arthur’s Pass crosses a huge landslide.

Ice
The main mechanism for ice transport is when glaciers act as “bulldozers”, pushing and grinding rocks ahead and aside to form moraines. Quite a bit of rock gets incorporated into the glacier. If the glacier flows into the sea, the trapped rock can be carried a long way in the icebergs until they melt. They then get “dropped” onto the seabed and incorporated into whatever sediments are already on the seafloor. These rocks are usually conspicuously different from the surrounding sediment, and examples have turned up in sediments that have later been formed into rock and lifted up onto land. The term for these rocks is **dropstones**. Isolated large boulders pushed into place by glaciers and many kilometres from where they originated are called **erratic boulders.**

Lithification (also called *diagenesis*)

This is the term used to describe the conversion of sediment into rock. The first stage in the process is simply the rock being squeezed, so that the spaces between the grains (pore space) is reduced and the sediment becomes harder and rock-like. If there is a good variation in the particle size, rocks formed by this

The Moeraki boulders are a good example of the role of minerals cementing the grains together. They are an instance of *concretions.*

step alone can be fairly solid because smaller grains fit "between" larger ones . Much of the soft sedimentary rock called "papa", found from Taihape to Wanganui and north Taranaki, has only undergone this degree of lithification.

With more pressure, some mineral grains start to dissolve at the grain boundaries and be recrystallized into the pore space. This "cements" the grains together, producing a far harder (or more **indurated**) rock. The hard sedimentary rocks that make up New Zealand's main mountain ranges have undergone this degree of lithification, and in fact have begun the first step towards metamorphism because some new minerals have formed. New minerals formed before metamorphism are termed **diagenetic minerals**; zeolite and prehnite are two examples of such minerals and geologists tend to disagree whether rocks containing these minerals should be termed metamorphic or sedimentary.

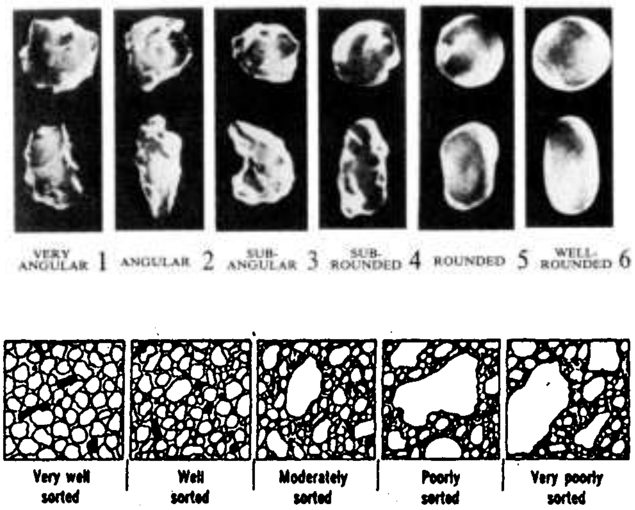
Calcite (shell) fragments become cemented together very readily even at quite shallow depths of burial, so can form hard limestones without getting very deep . However, for rock types other than limestones, the degree of induration (i.e the hardness) gives a rough guide as to how deeply the sediments have been buried.

Concretions: sometimes a small object, such as a piece of shell, in a sedimentary rock will act as a "seed" and minerals (usually calcite, but sometimes barite or limonite) will crystallize in the pore space around it, growing into the surrounding rock. The area where the mineral has crystallized is better cemented and therefore harder than the surrounding rock and will often be left behind after the rest of the rock has weathered and eroded away. The term for these "hard bits" in sedimentary rocks is **concretions.** If the surrounding rock is fairly uniform, the concretions will be quite spherical. However, they can assume other shapes if there are inhomogeneities in the surrounding rock. The Moeraki boulders are concretions which have weathered out of the cliff and been left lying on the beach. Barite concretions in Northland are sometimes mistaken for meteorites; there is an example of such a concretion outside the Waiomio Caves, north of Whangarei.

Classification of sedimentary rocks

One of the main criteria for classifying sedimentary rocks that are made up of rock or mineral fragments (termed *clastics)* is grain (particle) size. In order of increasing grain size, clastic rocks can be claystones, **mudstones**, **siltstones**, **sandstones**, gritstones, and **conglomerates** (bold type are the rocks mentioned in the AS). Clay and mudstones are smooth to the touch, siltstones just very slightly rough and sandstones sand-like. Gritstones contain grains a few millimetres in size and conglomerates gravel to boulder sized grains. Many sedimentary rocks contain a mix of grain sizes and shapes, and require some description. Geologists use comparison diagrams in the field to describe the grain size, roundness, smoothness and degree of sorting of the particles of sedimentary rocks which they encounter in fieldwork. A selection of these are shown in Figure 2.6.

Fig. 2.6
Angularity and sorting comparator sheets for sedimentary clastics.



Special classifications are used for rocks which are partly or wholly made of chemically deposited sediments such as limestones (>95% calcium carbonate) marls (mudstone with >50% carbonate), cherts, flints and so on.

Sedimentary environments

Certain types of sediment (or sedimentary rock) indicate particular environments of deposition.
Coal is formed in swamps or peat bogs. For plant matter to make up the bulk of the rock it requires a deficit of other sediment input, which implies a landscape of low relief.
Limestone also requires an environment with little other sediment input so that the main sediment forming material is the shells of marine organisms (shellfish, corals, bryazoa etc.), usually living in shallow and biologically rich seas. Coal and limestone are often found together when they were formed by an "old", worn-down landscape that was gradually being submerged to form shallow, sediment-poor seas or lagoons. The south-eastern USA is the sort of environment where coal and limestone form today: the swamps of the coastal states will eventually become coal and the coral of Florida limestone. Notice that this is well away from an area of volcanism or mountain building. Limestone can also be formed where strong currents sweep away sand and mud, leaving shells behind. The limestone on the southern end of Motoihe Island formed this way.

"Clastic" sedimentary rocks are formed by transported material. The finer the particle size, as a general rule, the greater the distance of transport. Coarse materials such as **conglomerate** or breccia indicate short transport distances and a landscape of high relief (mountainous) for the sediment source. Think of the Canterbury Plains as an example of this; when eventually the gravels form sedimentary rock they will vary from conglomerate size close to the Alps to sand sized on the quieter river meanders. Extremely poor sorting indicates a very high energy environment of deposition, such as a rock avalanche, a rugged mountain river or a rocky, exposed coast.

Extremely fine grained sedimentary rocks such as **siltstone** and **mudstone** imply long distances of transport and/or a low energy environment (e.g. slow moving water like a lake or an estuary, deep ocean). **Sandstone** is most often formed by underwater currents such as turbidity currents or currents on riverbeds. Sands with very even sorting of grain size and well rounded grains are characteristic of wind-blown deposits (e.g sand dunes,) though a geologist would look for other signs of wind deposition such as dune shapes in the bedding.

1. Describe the role of weathering and erosion in producing sediment. ....

Rocks weather to break down, then get worn away (erosion) to produce the material that is transported.

2. List the main transport mechanisms for sedimentary materials...

Wind, water (rivers, streams, turbidity current), ice, mass movement

3. Briefly describe how sediments are changed into rock.

As sediment is buried, the grains are pushed together by pressure and become cemented. Pore space is further filled by dissolved minerals to make the rock even harder.

4. Describe the sedimentary environment and origins for:

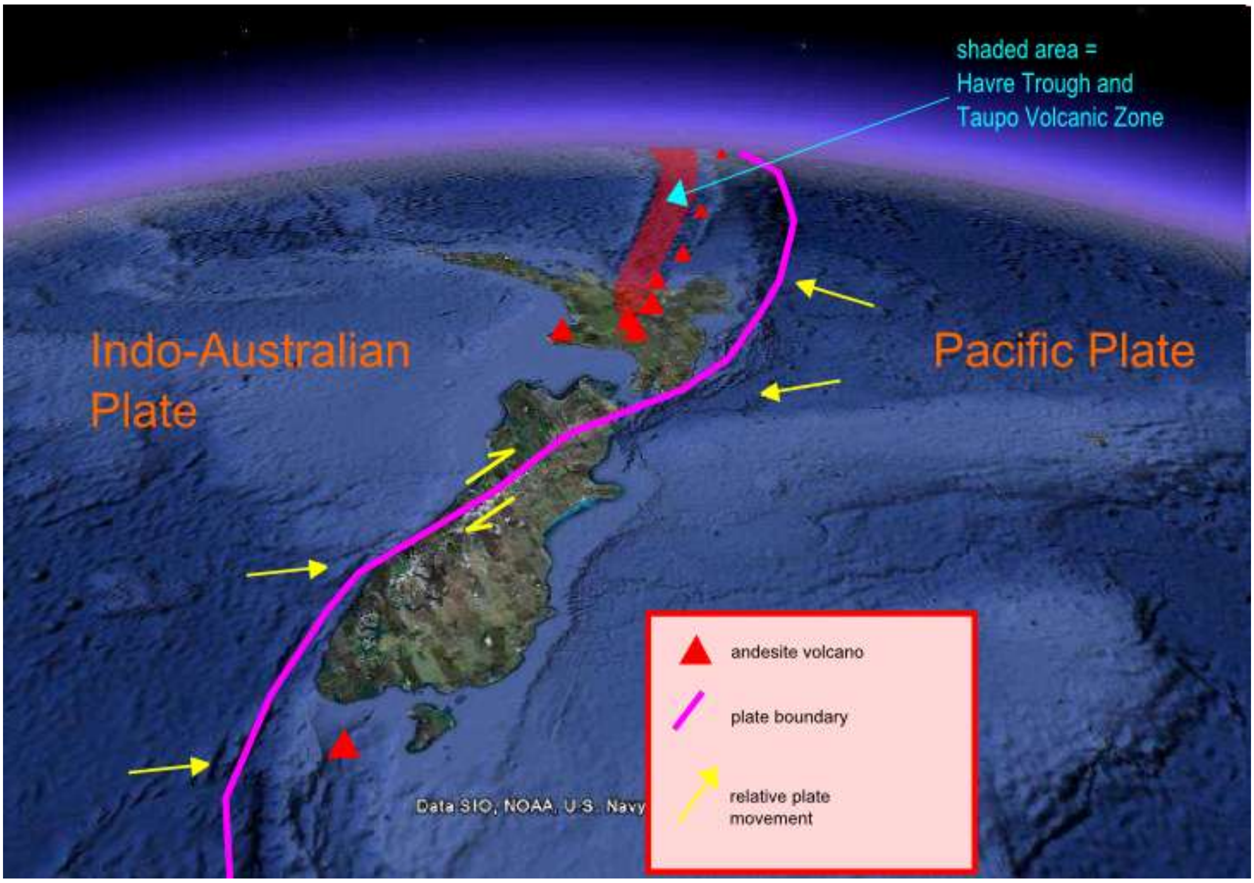
coal is formed in swamps which are starved of sediment input,

limestone is formed from shells, either in a sediment starved environment or one where sediment is removed by ocean currents to leave the shells behind., sandstone is formed by water flowing at several km per hour, either as rivers or streams or underwater currents (including turbidity currents), conglomerate is often related to mass movement e.g. landslide, lahar

5. Explain why the presence of limestone and coal imply a lack of relief in the landscape.

Both of these require a 'sediment starved' environment where there is no other sediment being deposited to 'mask' the input of living organisms (plants and shellfish). The main reasons for a lack of sediment are either that the landscape is so worn away that there is little erosion, or that the land is exceptionally dry so there is little water to weather/erode.

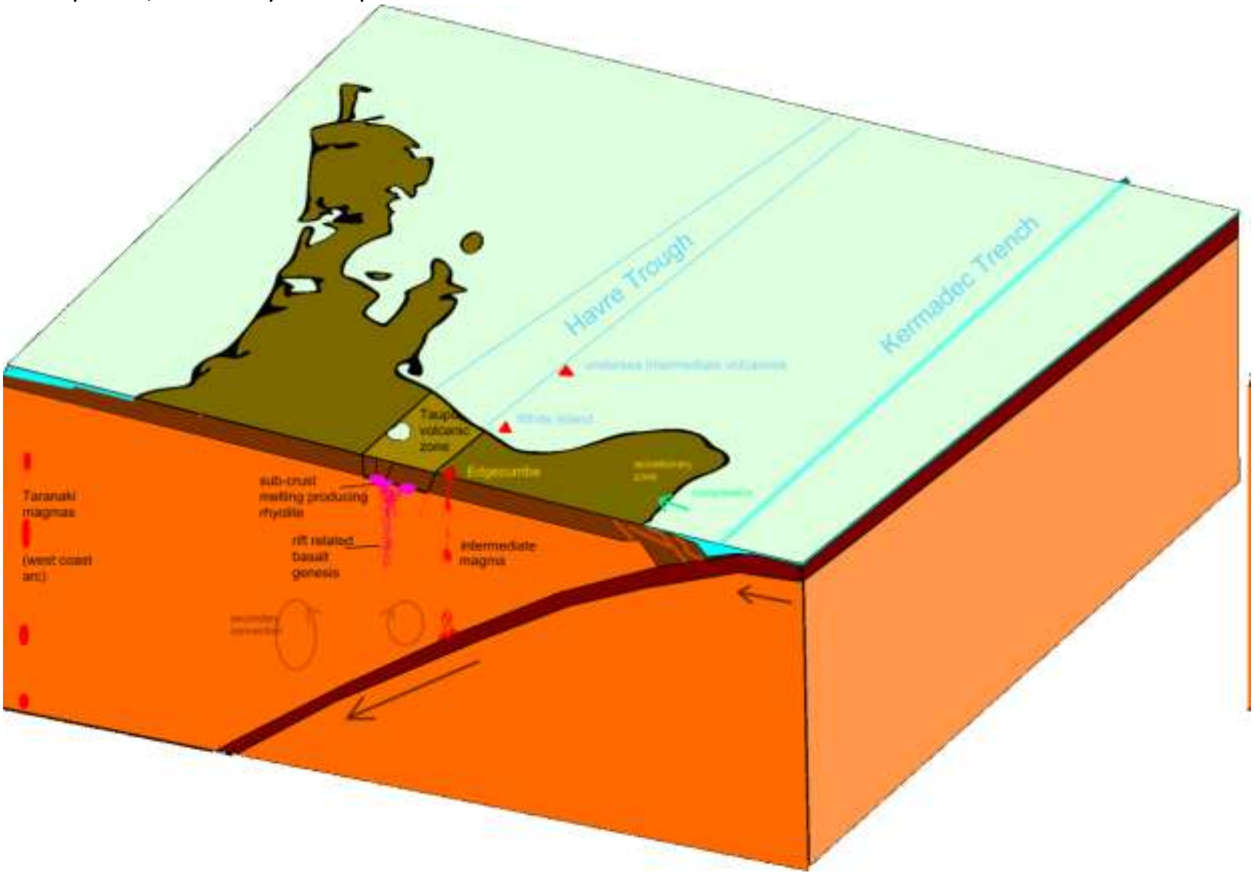
Plate tectonics in New Zealand



New Zealand lies on the boundary between the Pacific and the Indo-Australian plate:
boundary.png
From Mt Ruapehu to Tonga, the plate boundary forms a subduction zone. This subduction zone forms a continental arc from Ruapehu to White Island, and an island arc from White Island to Tonga.The forward edge of the arcs are marked by a chain of andesite and dacite volcanoes.
On land, the active or dormant volcanoes include: Ruapehu, Tongariro, Tauhara, Edgcumbe..There are numerous extinct ones, including some now buried beneath younger volcanics.
Offshore, the chain continues with islands - Whale Island, White Island, Raoul Island are all active/dormant. There are numerous submarine volcanoes in NZ territory, including Rumbles 1, II and III and the Brothers volcano.
Between Lake Rotorua and Lake Taupo lie a number of active and extinct caldera volcanoes, whose activity is probably related to back-arc rifting. The nature of the different types of volcanism will be discussed in more detail in the section on volcanoes.

.Adjacent to the volcanic arc is the Tonga-Kermadec trench. As the trench approaches NZ, it becomes shallower. This is mostly because it has filled up with sediment eroded from the North Island; the trench itself continues down to terminate off the coast of Kaikoura. In the area where the trench fills up with sediment, the sediment is pushed up onto land in the process of continental accretion. The East Coast of tne North Island is an example of such an accretionary prism.
Towards the Wairarapa coast, the subduction is no longer perpendicular to the plate boundary, and once it passes Mt Ruapehu there is no further volcanism. This is because the 'sideways' component of the subduction is so great that the subducted slab no longer sinks at a rate sufficient to engender the processes that trigger melting. However, as the vector of plate movement is changing with time, it is possible that new volcanoes will eventually appear to the south of Ruapehu.
The subducting slab continues to have an effect on the overlying lithosphere south of the TVZ, producing a large depression south of Taranaki: the Wanganui bight. Here, the basement rocks are dragged down to a depth of nearly 7 km and the depression is filled with huge thicknesses of young sediment. Inland, these

young sediments have been upwarped in the vicinity of Taihape, so that very young marine sediments (2-3 million years) are now over 500m above sea level. The rapid burial then exhumation of these sediments has produced rocks with some unusual mechanical properties, which causes considerable land stability problems in the area. Wanganui is also the location of New Zealand's most frequent very deep earthquakes, caused by these processes.



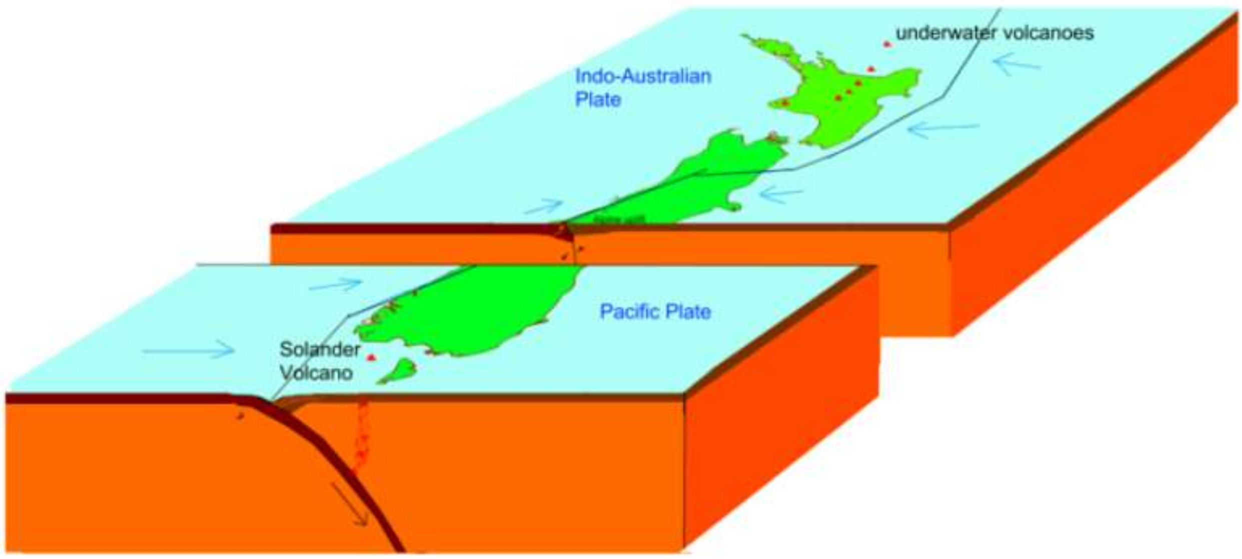
Further south, the Pacific plate no longer fully slides under the Australian plate. Instead it thickens the crust, and as a result the mountains grow increasingly large as you move towards the Alpine Fault. By the time the plate boundary reaches the Alpine Fault, there is no subduction, but the remaining compression helps push up the Alps.

Subduction resumes just south of Fiordland. The subduction here is much steeper than in the north, producing high pressure metamorphic rocks called eclogites at depth. The mineral changes in the descending lithosphere do not produce as much water, resulting in less volcanism. Only one volcano occurs south of the South Island, an andesite volcano at Solander Island. Although not presently active, this volcano may erupt again at some point in the future. Here, the Indo-Australian plate is subducted beneath the Pacific Plate.

Change-over: New Zealand therefore lies on the zone where the plate motion “changes over” from one direction of subduction to the other. Along about 200 km of the Alpine Fault, the plates slide past each other like this are known as transform plate boundaries.

Intra-plate volcanism: Not all volcanism is associated with a plate boundary. The Auckland and Kaikohe volcanic fields are active intra-plate or 'hot-spot' volcanoes, although not all geologists support hot spots as an explanation for these. Past instances of intra-plate volcanism in NZ include the Banks Peninsula volcanoes, basalts near Timaru, basalts on the Chatham Islands and the Otago Peninsula. Intraplate volcanism is dominated by basalt.

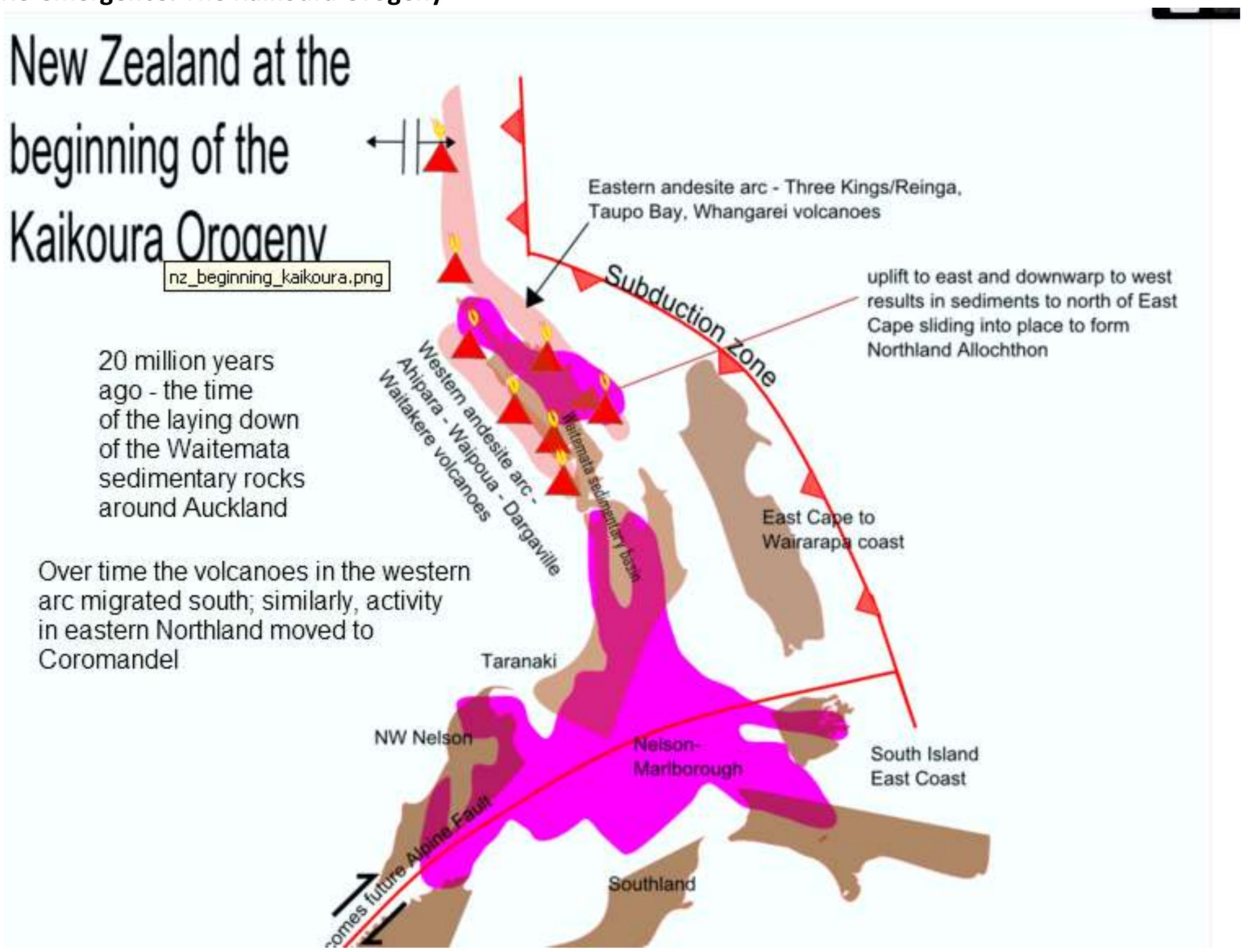
Plate movement and subduction
in the South Island



In the past:
New Zealand is the emergent part of a submerged continent called Zealandia, that has been formed over a period of 500 million years. It was once part of the Gondwana supercontinent, and split off 80-60 million years ago when the Tasman sea formed.
Deposition and uplift
The rocks that form Zealandia have been formed by cycles of deposition, alternating with periods of uplift called orogenies. An orogeny is a period of 'mountain building', during which the main processes are uplift (forming land and mountains), volcanism, intrusion, regional metamorphism. Orogenies are often signalled in the geological sequence by widespread unconformity, and the presence of high energy sedimentary rocks such as breccias and conglomerate as well as volcanic, intrusive and metamorphic rocks. Orogenies occur due to the presence of a convergent plate boundary.
The Tuhua depositional period and orogeny.
Before the first orogeny, Zealandia (together with parts of Australia and Antarctica) was entirely underwater. Sediment eroded from Gondwana, to the 'west' of this underwater region, was deposited in a huge 'basin' off Gondwana's "east coast", starting about 500 million years ago. About 400 million years ago, a chain of island volcanoes in this basin signalled the start of convergent tectonic activity, and this escalated until about 370 million years ago when the whole area was uplifted to become land. Remnants of this land are found today in NW Nelson and Fiordland, as well as in eastern Australia and Antarctica. This first period of uplift is called the Tuhua Orogeny.
Rangitata Depositional period and orogeny
The rocks uplifted by the Tuhua Orogeny eroded away, depositing sediment in a basin to the 'east', sometimes called the 'New Zealand Geosyncline'. These sediments were deposited by underwater currents, and form huge thicknesses of alternating sandstone and mudstone collectively known as 'greywacke'. They are hard, grey in colour and have been partly metamorphosed - the schists of Otago and elsewhere are these same sediments, fully metamorphic (deeper in the 'pile').
These sediments in turn was uplifted about 130 million years ago in the Rangitata Orogeny. This was followed by an extensive wearing down of the landscape to a nearly flat surface called a peneplain.
Opening of the Tasman Sea
About 80 million years ago a rift valley formed on 'east' of Gondwana. A chunk of eastern Gondwana split off and began to drift away, forming the Tasman Sea and the mini-continent of Zealandia. This continent extended from what is now the Auckland Islands in the south to New Caledonia in the north. The Tasman took some 20 million years to form.
Drowning

Following the opening of the Tasman, Zealandia continued to wear away. It became swampy, forming extensive coal deposits, then gradually sank below the sea. The drowned continent was a shallow and biologically rich sea, full of shells which eventually became limestone. Land life probably clung on in a few scattered islands and sandbanks.

Re-emergence: The Kaikoura Orogeny



About 22 million years ago, the pace of tectonic activity stepped up again. Parts of Zealandia rose out of the sea again, and a chain of volcanic islands formed in what is now Northland. New sedimentary basins formed, which sand and mud eroded from the newly emerged land rapidly began to fill. About 5 million years ago, part of the new plate boundary became a transform fault – the Alpine Fault. Hundreds of kilometres of sideways movement ensued, but a few percent of this movement was vertical and pushed up the Southern Alps.

Ice Ages

About 2 million years ago the Earth entered a period of cold and warm cycles called the Ice Ages. Sea level fell from an initial level some hundred or so metres higher than present to below where it is today, then rose and fell again and again at least eight times. Each time, the new high was a little lower than before. The low periods were called glaciations and were accompanied by the formation of extensive glaciers in Fiordland, the Alps and the central North Island. The last glaciations ended some 12,000 years ago and the sea level rose from 120 metres lower than today back to its current level. These periods between glaciations are called interglacials, and the sea level has started to rise again because human activity has interrupted the natural cycle.